EVALUATING DUST PALLIATIVE PERFORMANCE AND LONGEVITY USING THE UAF-DUSTM

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A

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Abstract

Fugitive dust emissions from gravel surfaces such as unpaved roads and airport runways are a major source of particulate matter pollution in the environment. Fugitive dust emissions impact community health, decrease visibility and contribute to surface degradation.. Chemical additives, also known as dust palliatives, are often used to reduce these dust emissions. Although these products have been widely used, little is known about their effectiveness and longevity. There is currently no standard test method to quantify the reduction in fugitive dust emissions provided by dust palliatives. The UAF-DUSTM was developed to provide a consistent test method for determining the effectiveness and longevity of dust palliative applications. Dust palliatives applications throughout Alaska were monitored for several years. The results show that dust palliatives can significantly reduce particulate matter emissions and be effective for several years.

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1. Introduction

Fugitive dust emissions from gravel surfaces such as roads or airport runways impact public health, decrease visibility, and contribute to surface degradation. Fugitive dust emissions are quantified as particulate matter with an aerodynamic diameter of 10 microns or less (PM_{10}). The United States Environmental Protection Agency (USEPA) limits the allowable ambient PM_{10} concentration to 150 μg/m^3 per 24-hour period. This limit is part of the National Ambient Air Quality Standards (NAAQS) established by the Clean Air Act (71 FR 61144). Areas exceeding this limit are classified as non-attainment areas and must implement various control strategies to reduce concentrations to attainment levels. PM_{10} typically accounts for 52.3% of the total suspended particles from roads. Unpaved road dust emissions account for 41.3% of the total PM_{10} emissions in the United States. This is greater than any other source, including industrial, agricultural, and natural windblown emissions (Watson et al., 2000).

Communities throughout Alaska experience the problems associated with fugitive dust emissions (Withycombe and Dulla, 2006). There is an extensive system of unpaved gravel transportation infrastructure throughout the state of Alaska. According to the 2010 Certified Public Road Mileage Report published by the Alaska Department of Transportation and Public Facilities (AKDOT&PF) there are 4,511 miles of unpaved public roads within Alaska. Unpaved roads represent 53% of the total 11,006 miles of public roads in Alaska. The AKDOT&PF also owns and maintains 252 rural airports, most of which are unpaved. Calcium chloride and magnesium chloride have been used throughout Alaska by AKDOT&PF to reduce fugitive dust emissions from unpaved roads. However, these traditional dust palliatives cannot be used on unpaved runways due to their potential corrosive nature. The AKDOT&PF has started to use nontraditional chemical dust palliatives throughout the state on rural unpaved runways. However, there is little knowledge of how these dust palliatives will work and how long they will be effective in the unique climates of Alaska.

Besides publications produced by dust palliative manufacturers, there are few guidance documents available to aid engineers in the selection, application, and maintenance of palliatives. There is no standard method to test the effectiveness of dust palliatives. From a construction standpoint it is difficult to hold a contractor to a performance specification when there is no means to determine the success of the application. Also, from an industry standpoint it is difficult to prove quantitatively the effectiveness of different dust palliatives. There is little known about the longevity of these palliatives once they have been applied. From an engineering standpoint, it is critical to know how well a dust palliative will work for a given site and how long the palliative application will be effective.

1.1 Objective

The objective of this study was to quantitatively measure dust palliative performance and monitor the longevity of dust palliative applications throughout Alaska. To accomplish this objective a new instrument, the UAF-DUSTM, was developed to quantitatively measure dust palliative performance. A corollary objective in this thesis was to develop the methodology for the UAF-DUSTM. Dust palliative performance was monitored from 2009 to 2012 at several sites. The results of this research will aid engineers in the selection of proper dust management strategies.

2. Background

2.1 Formation of Fugitive Dust

Unpaved roads are an unlimited reservoir of potential dust emissions. Two major mechanisms cause dust emissions from gravel roads: resuspension by vehicle induced turbulence and resuspension by tire shear. Wind erosion is another cause of road dust emissions, but does not contribute significantly compared to the mechanisms related to vehicle traffic. There is a large body of literature related to the resuspension of particles from surfaces by turbulence because of the various industrial applications. Small particles are adhered to a surface by electromagnetic forces including covalent bonds, charge interaction, van der Waals forces, and repulsive forces. In order for a particle to be resuspended by a turbulent fluid these forces must be overcome (Ziskind et al., 1995). Particles may also be adhered by capillary forces in the presence of a fluid. Fluids form liquid bridges that agglomerate particles to each other, thus increasing the particles size and resistance to resuspension.

Mollinger et al. (1993) investigated how vehicle shape, velocity, and distance from the ground affect particle resuspension by turbulent forces. All three factors were investigated using a pendulum passing over a fixed aggregate sample. Three models of different shapes were placed on the bottom of the pendulum. The profile of each model was different to create different turbulent forces. The height of the model above the ground surface was adjusted as well as the speed at which the model travelled over the fixed sample. The samples were weighed before and after each test to determine the amount of material resuspended. The study concluded that the most particles were resuspended when the model was close to the sample, the sample consisted of larger particles, the surface was smooth, and the aerodynamic shape of the model was poor. The larger particles, greater than 100 μm, experience less cohesive forces and are easier to detach from the surface. On a rough surface larger particles shield the smaller particles from the turbulent forces thus reducing emissions. A smooth surface increases the particle's exposure to turbulent forces. The poor aerodynamic shape creates greater turbulence behind the model.

There is limited literature on the resuspension caused by tire shear. Nicholson and Branson (1990) investigated the mechanisms of particle resuspension by vehicle traffic. This study used fluorescently dyed particles of four nominal sizes between 5 and 20 μm diameter applied to a road surface. An ultraviolet lamp illuminated the particles after they were resuspended and a photomultiplier measured their fluorescence. Tests were conducted to determine the influence of vehicle induced turbulence and tire shear on resuspension. A midsized car traveled across the deposited particles at 64 km hr^{-1}. The vehicle drove alongside the deposited particles to determine the influence of turbulence on resuspension. The vehicle drove directly over the deposited particles to determine the influence of tire shear on resuspension.

Based on the results, Nicholson and Branson concluded that the resuspension of 9.5 μm diameter particles and larger by tire shear and vehicle induced turbulence followed similar trends. The percent of fluorescent particles lofted after one vehicle pass was approximately 50% for the tire shear and vehicle induced turbulence experiments. Tire shear lofted 60% of fluorescent particles after three passes. Vehicle induced turbulence lofted 55% of particles after three passes. After ten passes both methods of resuspension failed to loft more fluorescent particles. Resuspension of particles smaller than 9.5 μm in diameter was more influenced by tire shear. The direct abrasion of large gravel particles caused by tire shear also replenishes material lost due to emissions (Watson et al., 2000).

Gillies et al. (2005) investigated how particulate emission from unpaved roads are effected by vehicle characteristics and weight. Nine vehicles traveling between 15 mph and 80 mph were used to generate particulate emissions from a gravel road. Vehicle weights ranged from 1.3 tons for a small sedan to 19.5 tons for a military off road cargo vehicle. The plumes of PM_{10} generated by the vehicles were sampled by three stationary towers downwind of the roadway. The experiments demonstrated that there was a linear relationship between vehicle speed and PM_{10} emissions. A linear relationship between vehicle weight and PM_{10} emissions was also found. Previous studies suggested that both relationships followed a power function.

The USEPA has published emissions factors for modeling particulate emissions from unpaved roadways in AP-42 (USEPA, 2011). The calculated emissions factor, in pounds per vehicle mile travelled, depends on the moisture content of the surface, mean vehicle speed, mean vehicle weight, and surface material silt content. There are separate formulas for calculating particulate emissions from industrial and public access roads. Emissions from industrial roads were found to depend more on the vehicle weight, while emissions from public access roads were found to depend more on the moisture content of the road surface. Empirical constants are used to correct for the size range of the particle. Emissions can be calculated as Total Suspended Particles, PM_{10}, or $PM_{2.5}$.

2.2 Managing Fugitive Dust Emissions

There are several ways to reduce the fugitive dust emissions from unpaved surfaces. Proper road design and construction are essential in reducing dust emissions. Institutional controls, such as reducing speed limits and restricting vehicle weights, are the cheapest methods of dust control, however they are difficult to enforce. Watering also provides dust control, but requires frequent application due to evaporation from the surface. Chemical additives, or dust palliatives, can be applied to or incorporated into the unpaved surface. Dust palliatives fall into several categories depending on their chemical components and the soil properties they change to reduce emissions. There is a significant cost associated with dust palliatives compared to other control measures. However, dust palliatives may offer a long term solution to dust problems when applied correctly.

Proper design and construction of unpaved roads and runways can help reduce fugitive dust emissions. The gradation of the material used for construction affects the potential dust emissions. The cohesive force between the fine particles and the internal friction between the coarser particles binds the material together (FCM, 2005). Poorly graded materials will not bind together and are easily resuspended by tire shear and turbulence. Well graded materials will form a solid matrix that resists deformation and resuspension of fine particles. Proper drainage is also necessary to avoid a reduction of fines due to washing, decreases in bearing capacity, and leaching of soluble dust palliatives (Foley et al., 1996).

As defined by AP-42 fugitive dust emissions are a function of vehicle speed, vehicle weight, and traffic type. Adjusting these parameters using institutional controls can reduce dust emissions. For example, by reducing speeds from 40 MPH to 20 MPH fugitive dust emissions can be reduced by 65% (Succarieh, 1992). Restricting vehicle access to certain unpaved roads within a road network based on vehicle weight or type may also reduce dust emissions. For example, restricting road access in industrial areas to only necessary equipment will reduce traffic volumes and total dust emissions (Countess Environmental, 2006). Institutional controls may be the most cost effective option but cannot be guaranteed to reduce dust emissions. Community cooperation or law enforcement is required for these management strategies to be effective.

If the unpaved surface has been properly constructed and institutional controls are not viable or effective, dust palliatives can be used to reduce dust emissions. Dust palliatives can be divided into several categories based on the soil properties they alter or their chemical constituents. Bolander and Yamada (1999) divide dust palliatives into seven categories: water, water absorbing products, petroleum based products, organic nonpetroleum based products, electrochemical products, polymer products, and clay additive products. Selection of the proper dust palliative depends on several site specific factors including soil gradation, traffic volume, traffic type, local climate, and the level of dust emission reduction desired.

Table 1 was developed by Bolander and Yamada to aid in the selection of dust palliatives depending on the site characteristics.

Table 1 - Palliative selection chart developed by Bolander and Yamada. (1999).

	Traffic Volumes, Average Daily Traffic			Surface Material								Climate During Traffic		
				Plasticity Index			Fines (Passing 75μm, No. 200, Sieve)							
Dust Palliative	Light <100	Medium 100 to 250	Heavy >250 (1)	<3	3–8	>8	<5	5–10	10–20	20–30	>30	Wet &/or Rainy	Damp to Dry	Dry (2)
Calcium Chloride	✓✓	✓✓	✓	✗	✓	✓✓	✗	✓	✓✓	✓	✗ (3)	✗ (3,4)	✓✓	✗
Magnesium Chloride	✓✓	✓✓	✓	✗	✓	✓✓	✗	✓	✓✓	✓	✗ (3)	✗ (3,4)	✓✓	✓
Petroleum	✓	✓	✓	✓✓	✓	✗	✓ (5)	✓	✓ (6)	✗	✗	✓ (3)	✓✓	✓
Lignin	✓✓	✓✓	✓	✗	✓	✓✓ (6)	✗	✓	✓✓	✓✓	✓ (3,6)	✗ (4)	✓✓	✓✓
Tall Oil	✓✓	✓	✗	✓✓	✓	✗	✗	✓	✓✓ (6)	✓ (6)	✗	✓	✓✓	✓✓
Vegetable Oils	✓	✗	✗	✓	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓
Electro-chemical	✓✓	✓	✓	✗	✓	✓✓	✗	✓	✓✓	✓✓	✓✓	✓ (3,4)	✓	✓
Synthetic Polymers	✓✓	✓	✗	✓✓	✓	✗	✗	✓✓	✓✓ (6)	✗	✗	✓	✓✓	✓✓
Clay Additives (6)	✓✓	✓	✗	✓✓	✓✓	✓	✓✓	✓	✓	✗	✗	✗ (3)	✓	✓✓

Legend

✓✓ = Good ✓ = Fair ✗ = Poor

Notes:

(1) May require higher or more frequent application rates, especially with high truck volumes
(2) Greater than 20 days with less than 40% relative humidity
(3) May become slippery in wet weather
(4) SS-1 or CSS-1 with only clean, open-graded aggregate
(6) Road mix for best results

Table 2, produced by the Federation of Canadian Municipalities (FCM), provides a summary of common dust palliatives, their source, how they reduce dust emissions, application, advantages, disadvantages, and environmental considerations.

Table 2 - Summary of dust palliative characteristics (FCM, 2005)

Types	Source	Functional Mechanism	Application	Performance Advantages	Performance Limitations	Environmental Considerations
Lignin derivatives	Paper-making industry by-product containing lignin and carbohydrates in solution. Specific composition depends on chemicals and processes used to extract cellulose.	Act as adhesives, binding road surface particles together.	■ Usually one to two treatments per year. ■ 10–25% solution 2.3–4.5 l/m².	■ Greatly increases dry strength of road surface materials. ■ Imparts some plasticity to road surfaces; lowers freezing point of road surface and base. ■ Effectiveness retained after reblading.	■ Can be leached out of the road during heavy precipitation ■ ($CaCO_3$ added ingredient, can neutralize acidity). ■ Proper aggregate mix (4%–8% fines) is important to performance. ■ Becomes slippery when wet, brittle when dry.	■ Lignin products have a high BOD (biological oxygen demand) in aquatic systems. ■ Spills or runoff into surface or groundwaters may create low dissolved oxygen conditions that are detrimental to aquatic life.
Synthetic polymer emulsions	Synthetic formulations composed of polyvinyl acetates, vinyl acrylic copolymers, copolymer methacrylates, polybutadiene.	Binds road surface materials together by adhesion.	■ Usually one treatment lasts two years. ■ 40%–50% solution ■ 1.4–4.5 l/m².	■ Applicable to a range of emission sources ■ Functions well in sandy road surface materials. ■ Some types allow seeded vegetation to grow through the polymer matrix.	■ Require proper weather conditions and time to cure; may be subject to UV (sunlight) degradation. ■ Application equipment requires timely cleaning ■ No residual effective-ness after reblading.	None.
Bitumens, tars, and resins ■ Residual fuel oil ■ Technical white oils ■ Fuel oils #4, #5, #6	Petroleum, coal, and plastics industry by-products.	■ Asphalt and resinous products are adhesive. ■ Petroleum oil products coat road surface particles, increasing their mass.	■ Refer to manufac-tures guidelines.	■ Water insoluble when dry; provide a degree of surface waterproofing. ■ Good residual effectiveness.	■ Surface crusting, fracturing, and potholes may develop. ■ Long-term application may cause road to become too hard for reblading. ■ Will not prevent frost heave.	■ Application of used oils is prohibited. ■ Some petroleum-based products may contain PAHs.
Water	From surface, groundwater or potable sources.	Moisture wets surface particles, binding them together by the surface tension of the water.	■ Usually only effective from 1 to 12 hours.	■ Usually readily available, low material cost, easy to apply.	■ Evaporates readily and usually controls dust for less than 12 hours.	No environmental hazard, if not applied excessively.
Seawater	Sea	Moisture stabilizes fines. Contains small quantities of salt (mostly $MgCl_2$), which retain moisture in road surface.	■ Usually only effective for one day.	■ Low material cost. ■ Performs better than freshwater. ■ Need for reapplication is less than with freshwater.	■ Only available in coastal areas.	Repeated applications and long-term use may harm nearby vegetation and aquatic life

Table 2 Continued - Summary of dust palliative characteristics (FCM, 2005)

Types	Source	Functional Mechanism	Application	Performance Advantages	Performance Limitations	Environmental Considerations
Calcium chloride	Three forms: flake, ■ Type I, at 77% to 80% purity pellet, ■ Type II, at 94% to 97% purity. ■ Clear liquid at 35% to 38% solids.	■ Attracts and retains moisture at a relative humidity of 29% at 25°C and 20% humidity at 38°C. ■ Assists compaction. ■ Treated road can be regraded and recompacted with less concern for losing moisture and density.	■ Usually one to two treatments per year. ■ Initial application, flake: at 0.5 to 1.1 g/m^2. ■ Typical application 0.9 kg/m^2 liquid: 35% to 38% solution at 0.9 to 1.6 l/m^2. ■ Typical application is 38% concentrate applied at 1.6 l/m^2. ■ Follow-up: apply 1/2 to 1/3 initial dosage.	■ Retains moisture and attracts moisture from the air. ■ Lowers freezing point of water minimizing frost heave and reducing freeze-thaw cycles. ■ Increases compacted density of road material. ■ Effectiveness retained after reblading.	■ Slightly corrosive to metal, highly to aluminum and its alloys. ■ Rainwater tends to leach out highly soluble chlorides. ■ If high fines content in treated material, the surface may become slippery when wet.	■ Repeated applications and long-term use may harm nearby vegetation and aquatic life. ■ Water quality impact: generally negligible if the proper buffer used. ■ Plant impact: some species are susceptible, such as, pine, hemlock, poplar, ash, spruce, and maple.
Magnesium chloride	■ Produced from natural salt brine. ■ By-product of potash production .	■ Attracts and retains moisture at a relative humidity equal to or greater than 32% independent of temperature. ■ More effective than calcium chloride solutions for increasing surface tension, resulting in a very hard road surface when dry. Treated road can be regraded and recompacted with less concern for losing moisture and density.	■ Usually one to two treatments per year. ■ Initial application: 28%– 35% solution. ■ Typical application 1.4 to 2.3 l/m^2 ■ Follow-up: 1/2 initial dosage	■ Reduces evaporation rate of moisture in the road. ■ Lowers freezing point of water minimizing frost heave and reducing freeze-thaw cycles. ■ Increases compacted density of road material, more so than $CaCl_2$.	■ Corrosive to steel, though inhibitors can be added. ■ Solubility results in leaching during heavy precipitation.	■ Repeated applications and long-term use may harm nearby vegetation and aquatic life.

2.3 Quantifying Fugitive Dust Emission from Gravel Surfaces

The USEPA has approved standard and equivalent methods for measuring ambient PM_{10} concentrations to determine compliance with the NAAQS. The standard method uses high volume samplers (Hi-Vols) to deposit particulate matter on a filter cartridge for 24 hours. After the sample period the filters are weighed and the average concentration is calculated based on the volume of air sampled (Center for Environmental Research Information, 1999a). The equivalent methods continuously measure atmospheric PM_{10} concentrations based on two principles. The first equivalent method monitors the attenuation of beta radiation through a paper filter. Particulate matter is deposited on the surface of the paper filter which increases the attenuation of the beta particles. The second equivalent method monitors the changes in resonance of an oscillating tapered element. The resonance changes as particulate matter is deposited on the element (Center for Environmental Research Information, 1999b). These instrumental methods measure total ambient PM_{10} concentrations and cannot be used to directly measure the emissions from a gravel surfaces.

Several stationary and mobile techniques have been developed to measure fugitive dust emissions from unpaved surfaces, but a standard method has not been established. Cowherd et al. (1974) conducted a study to establish the first fugitive dust emission factors for the USEPA. This report includes a review of the earliest fugitive dust measurement techniques prior to 1974. Cowherd et al. measured the concentration of total particulate matter 30μm in diameter or less (PM_{30}) in dust plumes generated by passenger cars and trucks adjacent to an unpaved road surface. Hi-Vol samplers were used as well as exposure profilers developed by the Midwest Research Institute (MRI). The MRI exposure profilers were designed to avoid the particle size bias associated with Hi-Vol samplers. Based on the results, Cowherd et al. concluded that the dust emissions were directly proportional to average traffic speed and the silt content. However, the emissions factors presented did not account for moisture content, vehicle weight, or traffic type (i.e. industrial vs. public).

In a report prepared for the California Regional Particulate Air Quality Study, Watson et al. (1996) demonstrated the effectiveness of fugitive dust control methods for unpaved roads and shoulders. This report includes a review of 16 previous dust demonstrations which were used to develop the testing strategy. Between July 1995 and August 1996, three different dust palliatives were monitored to determine their efficiency in reducing PM_{10} emissions in the San Joaquin Valley. For unpaved roads, samples were collected upwind, downwind, and directly overhead of the source to provide a complete characterization of the dust plume using Minivol portable PM_{10} samplers produced by AirMetrics. Meteorological conditions were monitored using a tower equipped with cup anemometers, wind vanes, temperature sensors, and humidity sensors. Surface properties of the test sections were characterized including: silt loadings, particle size distributions, moisture content, and surface strength determined using a penetrometer. The palliative efficiency was calculated as the percent reduction in emissions between an untreated control and the palliative treated sections. Gillies et al. (1999) used similar sampling techniques to study the effectiveness of four dust palliatives on public unpaved roads.

Sanders et al. (1997) developed a mobile measuring technique to study dust palliative effectiveness in Colorado. Their instrument, the Colorado State University Dustometer, consists of a high volume pump and filter cartridge attached to a pickup truck. The filter cartridge is placed three feet behind the left rear tire and one foot above the ground surface. As the truck travels across a test section the high volume pump is turned on and dust generated by the vehicle is deposited onto the filter. Filters are collected after each test and weighed in the laboratory. The mass of dust collected from a palliative treated section is compared to an untreated section to infer the dust emission reduction provided by the palliative. Rushing et al. (2005) used a similar mobile technique relying on gravimetric analysis of filters exposed to fugitive dust emissions behind a pickup truck.

Another mobile measuring technique, Testing Re-entrained Aerosol Kinetic Emissions from Roads (TRAKER), was developed by Kuhns et al. (2001) to provide real-time measurement of the PM_{10} emission potential based on the opacity of a sampled airstream for paved and unpaved roadways. The original TRAKER system used two TSI DustTrak Aerosol Monitors and a Grimm Particle Sizer mounted to a midsized vehicle. One DustTrak was attached to the hood of the vehicle. The other DustTrak was attached to an intake positioned behind the right front passenger tire. The PM_{10} emission potential of the road surface is calculated based on the difference between the dust concentrations measured behind the tire and the dust concentrations measured on the hood. The Grimm Particle Sizer was used to determine a mass distribution of the particles generated by the vehicle tire. Etyemzian et al. (2003) improved on the original TRAKER design. For the new TRAKER design samples were collected from in front of the vehicle bumper and behind both the right and left front tires. The sampled air passed through a plenum designed to distribute the sample between five instruments, however only two DustTrak instruments were used. Material losses within the sampling equipment were found to be insignificant. The TRAKER measurements were correlated to stationary monitors similar to those used by Gillies et al. and Watson et al. A similar mobile technique was developed by Edvardsson et al. (2009).

3. UAF-DUSTM

The UAF-DUSTM, shown in Figure 1, was developed with the goal of quantitatively measuring fugitive dust emissions from unpaved surfaces to determine dust palliative performance. The design of the UAF-DUSTM was driven by the need for a portable, user-friendly instrument that could easily be deployed in remote locations. The UAF-DUSTM uses a TSI DustTrak Aerosol Monitor to measure the mass concentration of PM_{10}, reported as mg/m^3, in the fugitive dust plume generated behind an all terrain vehicle (ATV). Concentration measurements are taken every second and recorded to the DustTrak's internal memory. Dust palliative performance may be determined based on its effectiveness at reducing PM_{10} emissions and the longevity of the application.

Figure 1 - The UAF-DUSTM. The instrument consists of a DustTrak Model II aerosol monitor and intake. The DustTrak is housed in a protective case, which is attached to the ATV. A plastic tube connects the intake to the DustTrak.

3.1 Equipment

3.1.1 TSI DustTrak Aerosol Monitor

PM_{10} concentrations are measured and recording using a DustTrak Aerosol Monitor produced by TSI, Inc. The first generation UAF-DUSTM used DustTrak Model 8520. The current setup uses a DustTrak II Model 8530. The theory of operation is the same for both devices. The mass concentration of particulates in a sampled airstream is determined based on opacity. As the sample enters the instrument it is split into two parts. One half of the sample is passed through a HEPA filter to remove particulates and used for sheath flow. The sheath flow keeps particulate contained in a steady stream and reduces contamination of the optics.

The other half of the original sample passes through an optics chamber. As shown in Figure 2, the optics chamber consists of a laser diode, gold plated mirror, and photo detector. The light from the laser diode pass through two lenses to create a sheet of light. The sheet of light then passes through the sample airstream. A fraction of that light is diverted by the particles in the sample and reflected off the gold plated mirror to the photo detector. The voltage across the photo detector is multiplied by a calibration constant to determine the mass concentration of the sample. The instrument is calibrated by TSI, Inc. using known concentrations of Arizona Test Dust. When the sample passes through the optics chamber it enters a gravimetric filter which can be used for further analysis of the sample (TSI, 2012). The DustTrak is returned to TSI, Inc. annually for calibration and any necessary repairs. The DustTrak can be equipped with PM_1, $PM_{2.5}$,

PM_4, and PM_{10} size selective inlets. The PM_{10} selective inlet is used for all UAF-DUSTM measurements.

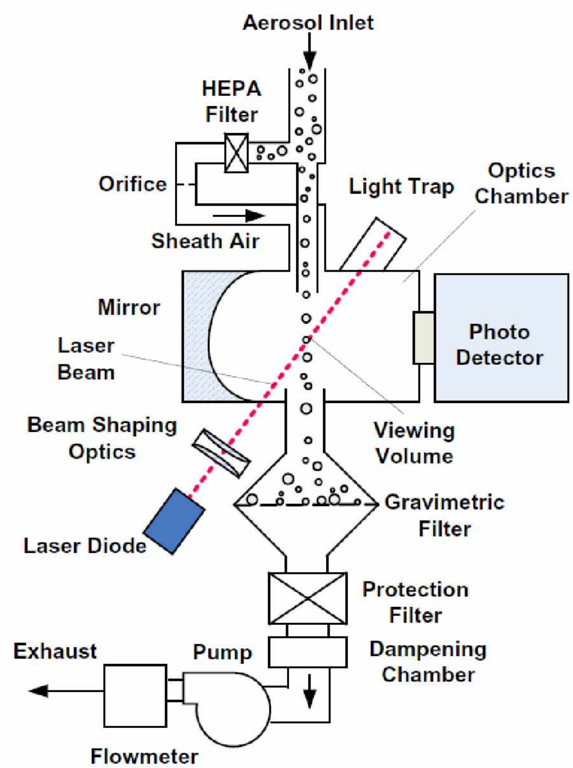

Figure 2 - TSI DustTrak Model II Aerosol Monitor flow schematic (TSI, 2012).

3.1.2 Intake

The original intake design is shown in Figure 3. This intake was designed to allow for simultaneous concentration measurements based on opacity and gravimetric analysis. Flexible tubing connected a DustTrak to the outlet on the top of the intake. The bottom of the intake structure contained a 37mm-filter cassette that was attached to a vacuum pump. It was initially assumed that the airflow into the intake was equal to the airflow out of the intake and that the concentration measurements were representative of the dust plume generated behind the tire. Tests revealed dust accumulated in the intake, which caused a continuous increase in concentrations and poor measurement resolution.

Figure 4 shows the current intake design. The plastic tube that connects to the DustTrak is centered on a 2-3/4 inch diameter flat aluminum plate. This intake provides higher measurement resolution and greater accuracy. Rather than capturing dust in a controlled volume, the intake allows for instantaneous sampling of the vehicle generated dust plume. Figure 5 shows a plot of PM_{10} concentration versus time for the original intake and the current intake designs over the same test section. The data for the current intake design shows more variation in concentrations, which indicates a higher resolution of measurement. The intake is installed on the opposite side of the ATV exhaust to avoid the exhaust influencing the measurements. The intake is connected to the UAF-DUSTM frame with three rigid aluminum pipes to avoid horizontal and vertical displacement during operation.

Figure 3 – The original UAF-DUSTM intake design.

Figure 4 - The current UAF-DUSTM intake design.

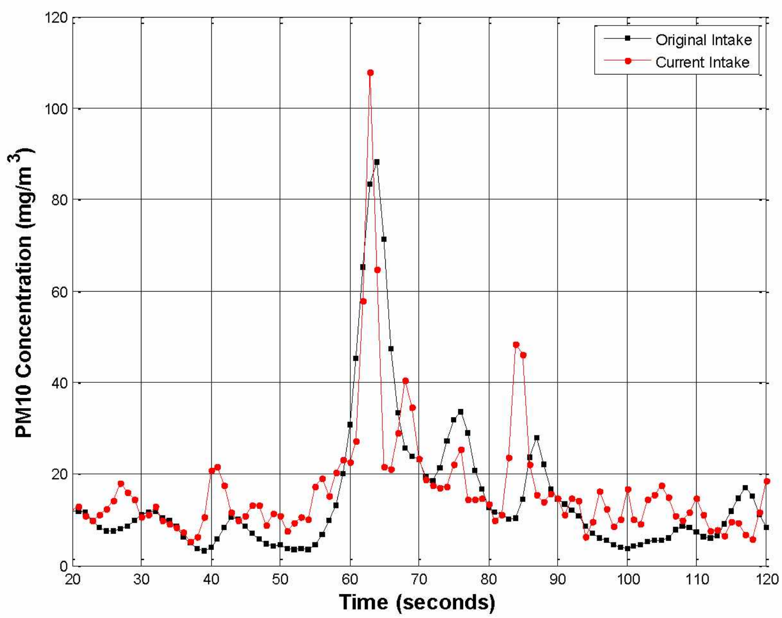

Figure 5 - PM_{10} Concentration vs. Time for the original intake and current intake designs.

3.1.3 All Terrain Vehicles (ATV)

The UAF-DUSTM was designed to mount onto any type of ATV. For test sites that are accessible by road a 2010 Polaris Sportsman 300 is used. The Sportsman 300 has an automatic transmission, digital speedometer, and can be driven in either 2-wheel or 4-wheel drive. During UAF-DUSTM testing 2-wheel drive is used. The stock front tire dimensions are 22x7-12 in the rear tire dimensions are 22x10-12. The Sportsman 300 has a dry weight of 500 pounds (Polaris, 2009).

The ATV must be rented in locations without road access. A variety of ATV's have been used at sites that do not have road access. The make, model, transmission type, position of the exhaust, and tire dimensions are recorded when using a rented ATV. Typically these ATV's do not have speedometers. If the ATV does not have a speedometer a handheld Garmin Oregon 550t GPS device is used to measure the speed of the ATV during tests.

3.1.4 Meteorological Station

A Kestrel 4500 Pocket Weather Tracker, manufactured by Nielson-Kellerman Company, is used to record meteorological data during testing. The Kestrel 4500 is mounted on a compact tripod with a wind vane mount. The weather station is placed adjacent to the testing area, away from any structures or vegetation that may influence measurements. The Kestrel 4500 is used to record: wind direction, wind speed, temperature, wind chill, relative humidity, heat index, dew point, and the wet bulb temperature.

3.2 Test Procedure

Test sections are selected to provide a representative sample of the dust palliative's performance. On airport runway applications, tests are performed along the centerline between the runway thresholds. The gravel surface outside of the runway lights is typically used for the control section. For roads, tests are performed within each travel lane. The length of road test sections depends on the length of the palliative treatment. A minimum length of 1000 feet provides a statistically sound sample size of at least 30 data points per test run. The beginning and end of the test section are clearly marked for reference. Adequate distance is required before and after each test section to allow safe acceleration and braking.

To begin testing, the ATV is positioned so the operator can accelerate to 20 mph before crossing the start of the test section. The DustTrak and stopwatch are started simultaneously. Synchronization is ensured by quickly comparing the stopwatch to the time displayed on the DustTrak. The operator gradually accelerates to 20 mph. The stopwatch's lap function is used to record the time between starting the DustTrak and reaching the beginning of the test section (T_1). A constant 20 mph is maintained with no rapid steering adjustments. At the end of the test section the lap function is used to record the length of time required for the test (T_2). Upon crossing the end of the test section the operator gently brakes. After the ATV has come to a complete stop the operator stops the DustTrak and stopwatch simultaneously and records the time (T_3). The test number, DustTrak log number, the average PM_{10} concentration, T_1,T_2, and T_3 are recorded in the waterproof log book.

At this point a single UAF-DUSTM test has been completed. The operator repositions the ATV and repeats the process, travelling in the opposite direction. A minimum of six tests, three in each direction, are conducted on both the palliative treated sections and the control sections. Between each test the equipment is visually inspected and repairs are made as necessary.

3.3 Data Analysis

After field tests are complete the data is downloaded from the DustTrak and analyzed. The data recorded during T_1 and T_3 are removed, as they are not representative of the dust palliatives performance. Only concentration data recorded during T_2 is used to determine dust palliative effectiveness and longevity. Several methods have been proposed to determine dust palliative effectiveness. This section provides a description of the proposed methods and a discussion of their limitations.

The first method calculated the PM_{10} emission reduction (%R) as follows:

$$\%R = \left(1 - \frac{\overline{C_T}}{\overline{C_C}}\right) * 100\%$$

Where, $\overline{C_T}$ is the average concentration measured on the dust palliative treated section, and $\overline{C_C}$ is the average PM_{10} concentration measured on the untreated control section. This method assumed the data collected came from a population fitting the normal distribution, and thus the average concentration values were valid descriptors of the data sets. Goodness of fit testing using the Kolmogorov-Smirnov Test (Massey, 1951) showed that the concentration data does not fit a standard normal distribution. Analyzing the concentration data using the Lilliefors Test (Conover, 1971) confirmed that the data does not fit any distribution in the normal family. Since the concentrations do not fit a normal distribution this analysis method was rejected.

The second proposed analysis method, called the S-Curve Method, was based on nonparametric order statistics. A complete series analysis was conducted on the concentration data collected from the treated section. The reduction of PM_{10} emissions for each descending ordered data point was calculated as follows:

$$\%R = \left(1 - \frac{C_{T_i}}{\overline{C_C}}\right) * 100\%$$

Where C_{T_i} is the i^{th} concentration measured on the dust palliative treated section, and $\overline{C_C}$ is the median concentration measured on the untreated control section. The points were then plotted against the cumulative percent surface area (%), which is calculated as follows:

$$\%A = \left(\frac{n - n_i}{n}\right) * 100\%$$

Where n is equal to the total number of datum points, and n_i is equal to the i^{th} data point.

Figure 6 is example of the plots developed using this analysis technique for data collected from Moosewalk Road in North Pole, Alaska, on two different dates. Dust palliative effectiveness is interpreted from the plot based on the percent reduction for a selected percent surface area. For example, on August 17th, 2010, 85% of the dust palliative treated surface area was reducing PM_{10} emissions by 95% or greater. However, on September 12th, 2010 the dust palliative was providing zero reduction in PM_{10} emissions over 85% of the surface area. Based on these results it would appear that the dust palliative's effectiveness had significantly decreased in less than a month.

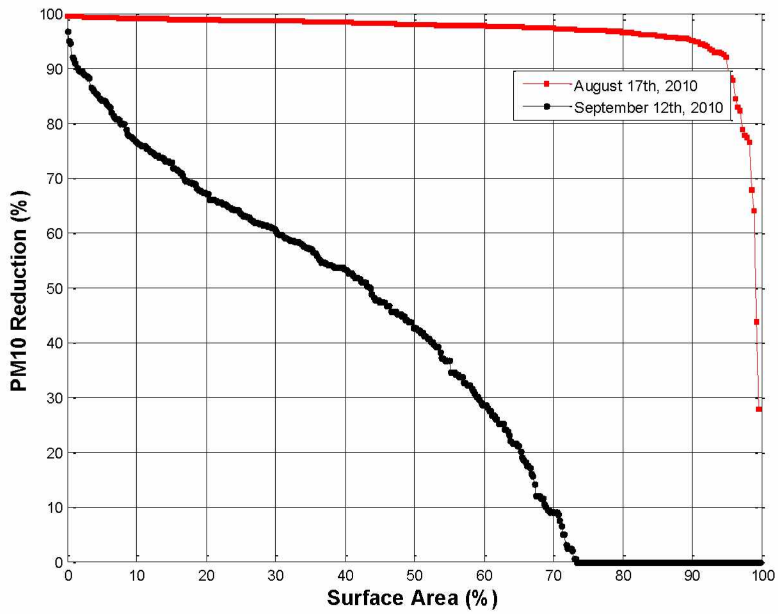

Figure 6 - Results from two UAF-DUSTM tests performed on Moosewalk Road in North Pole, Alaska, analyzed using the S-Curve Method.

Such a rapid decline in dust palliative effectiveness was not anticipated. Upon further analysis of the data it became clear that the concentrations measured on the dust palliative treated section were actually similar for both days. For example, the actual PM_{10} concentration corresponding to 85% of the surface area on August 17th, 2010 was 2.74 mg/m^3. The PM_{10} concentration corresponding to 85% of the surface area on September 12th, 2010 was 2.97 mg/m^3, which is only 8% greater than the concentration measured on August 17th. Figure 7 is a plot of the PM_{10} concentrations, in log scale, measured on the palliative treated section for both dates. Based on the figure, approximately 70% of the concentrations measured on August 17th, 2010 were greater than those measured on September 12th, 2010. This indicates that the dust palliative was still reducing PM_{10} emissions, even though the results of the S-Curve Method analysis suggest otherwise.

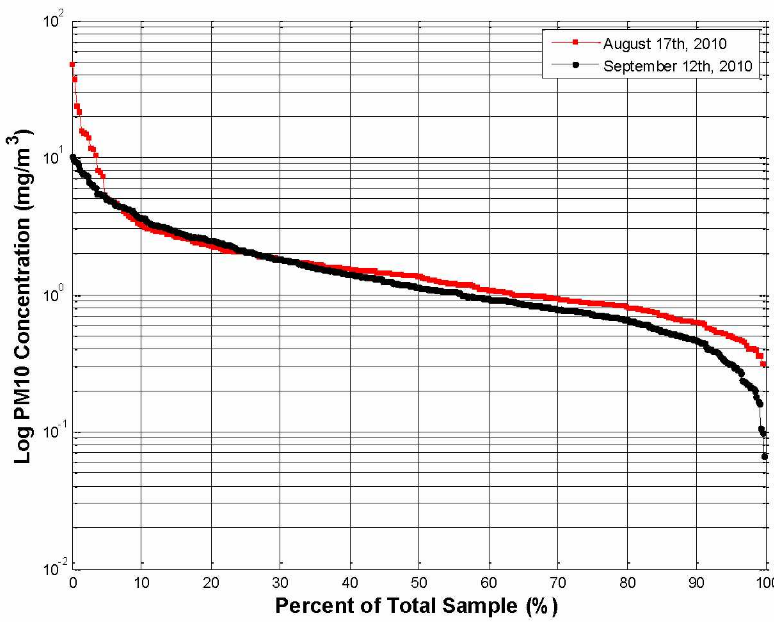

Figure 7 - Log PM_{10} Concentration vs. Percent of Total Sample for two UAF-DUSTM tests performed on Moosewalk Road in North Pole, Alaska.

This error was caused by the use of the median control concentration to calculate the dust palliative effectiveness. On 8/17/2010 the median control concentration 35.1 mg/m^3. On 9/12/2010 the median control concentration was 2.97 mg/m^3. The difference in median control concentrations between the two tests is due to an increase in moisture content caused by precipitation. The increased moisture content significantly reduced the PM_{10} emission from the control section on 9/12/2010. However, the increase in moisture content did not affect the PM_{10} emissions from the dust palliative treated section.

The discrepancy between how moisture content affects the palliative treated section and the untreated control section is most likely related to how dust palliatives behave in the soil matrix. Typically the soil matrix contains two fluids: air and water. In this case, water acts as the wetting fluid, spreading across the surface of the individual soil particles. In the presence of a solid surface a liquid will coat, or wet, the surface due to viscous forces and surface tension. The extent to which the liquid wets the solid surface depends on the interfacial tension between the solid-vapor phase (γ_{sv}), the solid-liquid phase (γ_{sl}), and the liquid-vapor phase (γ_{lv}). When (γ_{sv} - γ_{sl}) is greater than γ_{lv} the liquid will completely coat the solid surface. When (γ_{sv} - γ_{sl}) is less than γ_{lv} the liquid will not wet the surface (Kumar and Prabhu, 2007).

Capillary pressure is developed within the pore space due to the internal pressure difference between the two fluids. The magnitude of the capillary pressure depends on the curvature of the interface between the two fluids, which is a function of the interfacial tension (Bear, 1972). Capillary pressure, p_c, is defined as:

$$p_c = p_{nw} - p_w$$

Where, p_{nw} is the pressure in the nonwetting phase and p_w is the pressure in the wetting phase. Capillary pressure causes the wetting fluid to advance through the pore space and displace the nonwetting fluid. The interfacial tension between the soil particles and the wetting fluid, and the cohesive force of the fluid, holds the soil particles together.

Synthetic dust palliatives act as a third immiscible fluid when applied to an unsaturated soil. Again, the interfacial tension between the three fluids determines which fluid will be wetting with respect to the soil particles. It is still unclear whether the dust palliative acts as a wetting fluid or as an intermediate fluid between the water and air. However, it is clear that the introduction of a third immiscible fluid to the system will have an effect on the capillary pressure within the pore space based on the fundamentals discussed. The influence of the dust palliative on capillary pressure may explain why precipitation has a greater affect on the emissions from the control section rather than the palliative treated section, as indicated by these results. Further investigation of how synthetic dust palliatives behave within the soil matrix on a microscopic level is required but beyond the scope of this project. The S-Curve Method was rejected due to the possibility of incorrectly judging dust palliative effectiveness due to variations in moisture content.

The third proposed analysis method used the variance associated with each dataset to infer dust palliative performance and longevity. After the initial application of a dust palliative it was observed that there is little variation in PM_{10} concentrations measured from the surface if the palliative was applied properly. Figure 8 is a histogram of the PM_{10} concentrations measured on Sharon Road in North Pole, Alaska, two weeks after the initial palliative application. The dust palliative used was an immiscible fluid applied directly to the road surface. The PM_{10} concentrations are closely grouped with little variation, and a large peak in the data can be observed. It was proposed that as the dust palliative aged the variation in PM_{10} concentrations would increase.

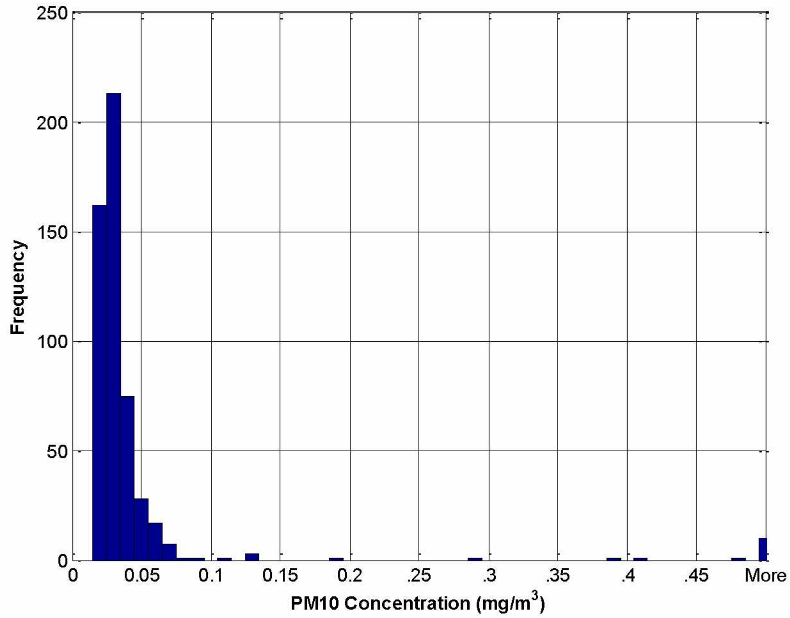

Figure 8 - Histogram of PM_{10} concentrations measured on Sharon Road, North Pole, Alaska. 8/12/2010

The median absolute deviation (MAD) was used to quantify the variance of the dataset. The MAD is accepted as a robust measure of variance, reducing the bias caused by extreme outliers on the calculation of variance (Hoaglin et al., 1982). Extreme outliers in the dataset are typically residuals of the concentrations measured during the acceleration and deceleration periods and are not representative of the dust palliatives performance as discussed previously. The MAD is calculated as:

$$MAD = median(|C_i - \bar{C}\,|)$$

Where C_i is the i^{th} concentration of the dataset C and $\bar{C}$ is the median concentration. To compare the MAD from each dataset the concentrations are normalized using the median concentration from the dataset as follows:

$$C = \frac{C_i}{\bar{C}}$$

Where C is the normalized concentration, C_i is the i^{th} data point, and $\bar{C}$ is the median. The concentrations are normalized so each dataset is on a similar scale and to reduce the influence of factors such as wind and weather. Figure 9 is a histogram of the normalized PM_{10} concentrations measured on Sharon Road in North Pole, Alaska, two weeks after the initial palliative application. The MAD for the normalized PM_{10} concentrations measured on 8/12/2010 is 0.2069.

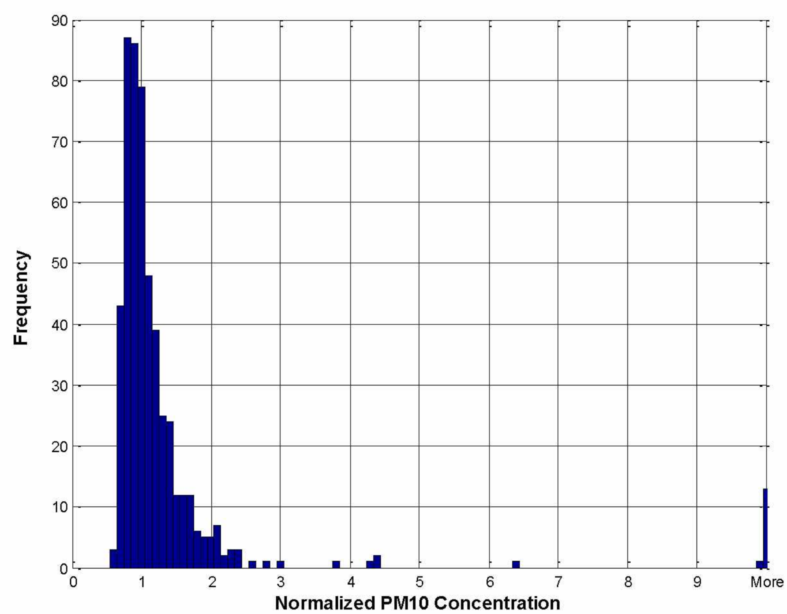

Figure 9 - Histogram of Normalized PM_{10} Concentrations for Sharon Road, North Pole, Alaska, on 8/12/2010.

Figure 10 is a histogram of the normalized PM_{10} concentrations measured on Sharon Road on 9/20/2010. Comparing Figure 9 and Figure 10 there appears to be an increase in the variability of the normalized PM_{10} concentrations. There is less peakedness in Figure 10than Figure 9, and the normalized PM_{10} concentrations are more dispersed. The MAD for the normalized PM_{10} concentrations measured on 9/20/2010 is

0.4524. This supports the assumption that variance is a good indication of decreasing dust palliative effectiveness.

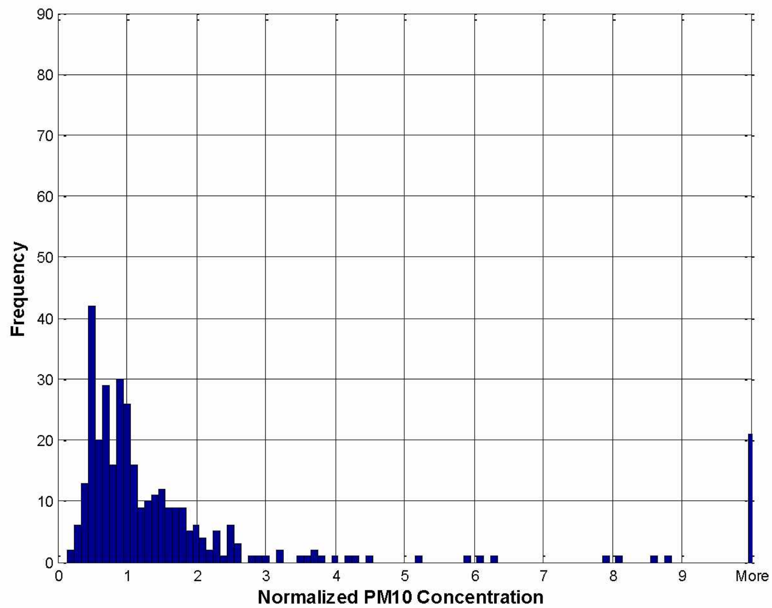

Figure 10 - Histogram of Normalized PM_{10} Concentrations for Sharon Road, North Pole, Alaska, on 9/20/2010.

Figure 11 is a histogram of the normalized PM_{10} concentrations measured on Sharon Road on 6/1/2011; nearly a year after the initial application was completed. Comparing Figure 10 and Figure 11 there appears to be a decrease in the variability of normalized PM_{10} concentrations. There is more peakedness in Figure 11 than Figure 10, and the normalized PM_{10} concentrations are less dispersed. The MAD for the normalized PM_{10} concentrations measured on 6/1/2011 is 0.3373. This is a decrease from the MAD for the normalized PM_{10} concentrations measured on 9/20/2010, contradicting the assumption that variability is a good indication of the change in dust palliative performance.

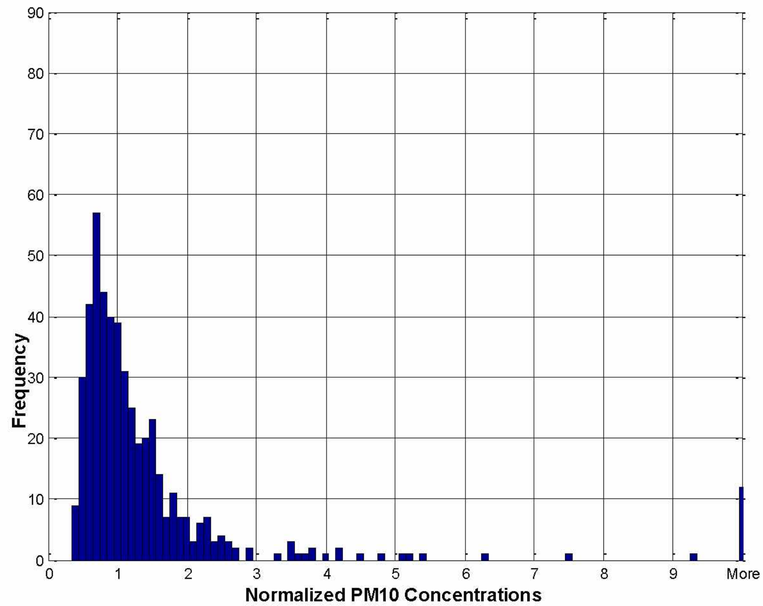

Figure 11 - Histogram of Normalized PM_{10} Concentrations for Sharon Road, North Pole, Alaska, on 6/1/2011.

Figure 12 is a plot of the PM_{10} concentrations, in log scale, measured on Sharon Road on 8/12/2010, 9/20/2010, and 6/1/2011. Despite the decrease in variance between the data collected on 9/20/2010 and the data collected on 6/1/2011, the figure indicates that the PM_{10} concentrations increased with time. Therefore, it was concluded that this method of calculating variation to describe how dust palliative performance changes with time is not a valid approach.

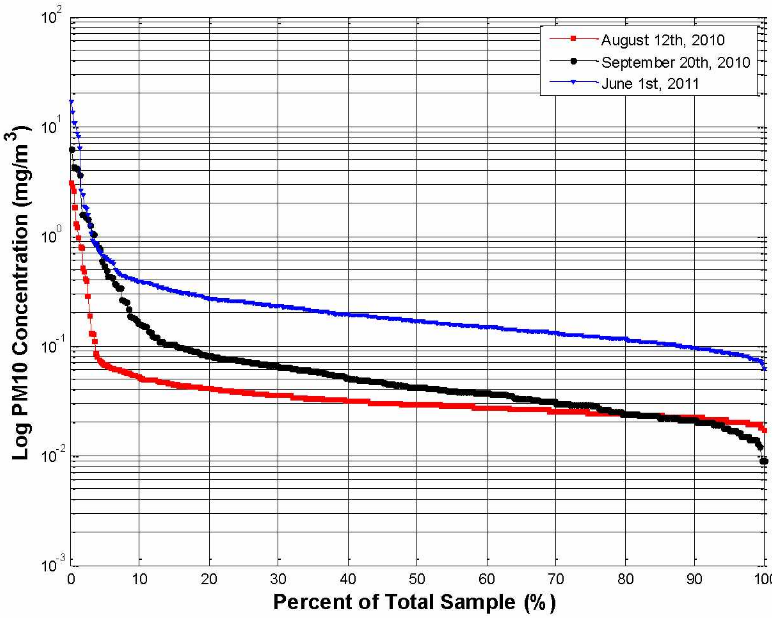

Figure 12 - Log PM_{10} Concentration vs. Percent of Total Sample for three UAF-DUSTM tests performed on Sharon Road in North Pole, AK. UAF-DUSTM tests were conducted on 8/12/2010, 9/20/2010, and 6/1/2011.

At this point there is no consistent method for quantifying the effectiveness of a dust palliative application using a single statistic. Calculating the dust palliative's effectiveness using a control section has proven to be inconsistent due to the difference in soil matrix behavior once a dust palliative has been introduced. Further investigation into how the introduction of a dust palliative influences the soil matrix is required, but is beyond the scope of this project. This fact makes it difficult to compare the performance of a dust palliative between sites in absolute terms. Also, a single statistic that consistently indicates dust performance and palliative longevity has not been found.

Rather than seeking a single variable to indicate dust palliative performance and longevity, the entire dataset of concentrations may be considered. As illustrated in Figure

7 and Figure 12, plots of the entire dataset of concentrations can be used to judge the difference in PM_{10} concentrations and infer dust palliative longevity.

Box plots are another useful tool for comparing concentrations between successive dates. Figure 13 is a box plot of the PM_{10} concentrations measured on Moosewalk Road in North Pole, Alaska, over a six week period. The box plot indicates the 25th percentile, 50th percentile or median and 75th percentile of the data. These values illustrate the variability in the dataset without normalizing the data. The whiskers extending from the box plot indicate the smallest and largest values that are not outliers. Based on this figure, a trend of increasing PM_{10} concentrations is evident. While the PM_{10} concentrations decrease between 8/17/2010 and 9/12/2010, also indicated by Figure 7, they significantly increase on 9/17/2010. Figure 14 contains a box plot of the PM_{10} concentrations measured on Moosewalk Road on 6/1/2011, nearly a year after initial application. This figure clearly indicates that the effectiveness of the dust palliative decreased between 9/17/2010 and 6/1/2011, confirming the trend indicated by Figure 13. Note that for these boxplots outliers are omitted for clarity.

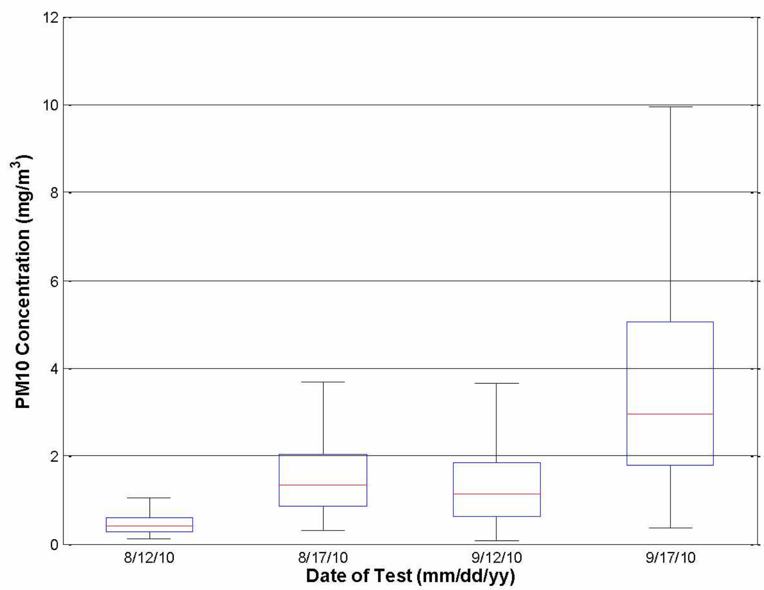

Figure 13 - Box plot of PM_{10} concentrations measured during four separate UAF-DUSTM tests on Moosewalk Road in North Pole, Alaska.

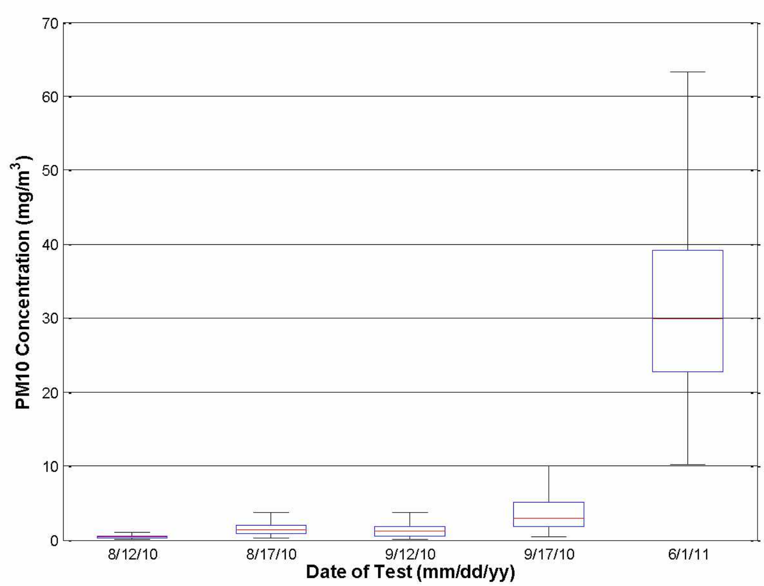

Figure 14 - Box plot of PM_{10} concentrations measured during separate UAF-DUSTM tests between 8/12/2010 and 6/1/2011 on Moosewalk Road in North Pole, Alaska.

3.4 Factors Affecting Measurements

During development of the UAF-DUSTM testing methodology several factors that influence test results were identified. Wind can significantly affect the dispersion of the dust plume behind the ATV. Concentrations tend to be higher when travelling into a headwind, and lower when travelling with a tailwind. This is due to the influence of the wind on the dispersion of the dust plume relative to the moving intake structure. When travelling into a headwind the ATV shields the dust plume generated by the tire from being dispersed. When travelling into a tailwind, the dust plume is not shielded by the ATV and can be dispersed by the wind.

Figure 15 is a plot of wind data recorded during a UAF-DUSTM test conducted on the runway in Tetlin, AK. The orientation of the runway is overlaid on the plot for reference. During this test there was a predominant headwind for all tests conducted travelling due east. Figure 16 is a plot of the PM_{10} concentrations recorded during this test which illustrate the affects of head and tail winds From the figure it can be seen that concentrations recorded while travelling into the headwind are higher than those recorded while travelling with a tailwind.

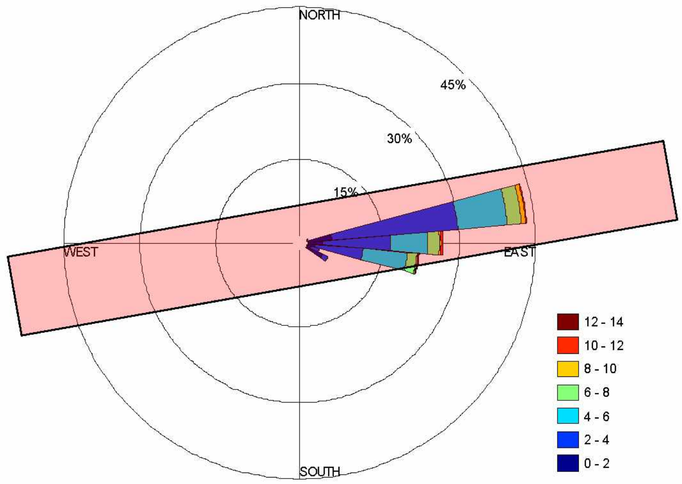

Figure 15 - Wind data in miles per hour recorded during a UAF-DUSTM test on the runway located in Tetlin, Alaska, in August 2010. The box overlaid on the plot represents the position of the runway relative to the wind data. This figure shows that there was a predominant head/tail wind during testing.

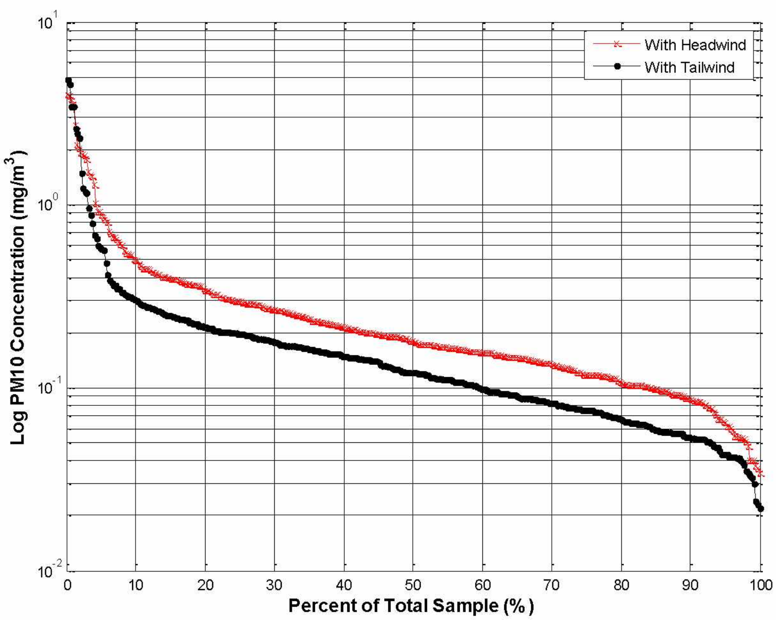

Figure 16 – PM_{10} concentrations recorded during UAF-DUSTM test performed on the runways in Tetlin, Alaska, in 2010. The concentrations recorded while travelling into the wind are greater than the concentrations recorded while travelling with a tail wind.

Cross winds also affect the PM_{10} concentrations recorded during testing. Figure 17 is a plot of wind data recorded during a UAF-DUSTM test performed in Casa Grande, AZ. The road being tested was aligned directly north and south. There was a predominant cross wind during these tests. Figure 18 shows the PM_{10} concentrations recorded during these tests. There is a significant difference in the North and South bound concentrations. The intake was positioned behind the right rear tire during testing. The dust plume generated by the tires was dispersed away from the intake when driving in the south bound direction. The wind dispersed the dust plume generated from the left tire towards the intake when travelling in the north bound direction the. The larger concentration readings were caused by the combination of the dust plumes from the right and left tire.

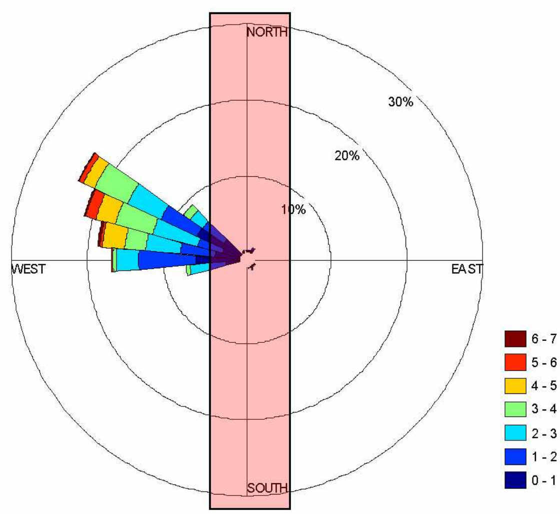

Figure 17 - Wind data in miles per hour recorded during a UAF-DUSTM test performed on Tweedy Road in Casa Grande, Arizona in January 2011. Tweedy Road travels in the north/south direction. The box overlaid on the plot represents the position of the road relative to the wind data. This figure shows that there was a predominant crosswind during testing.

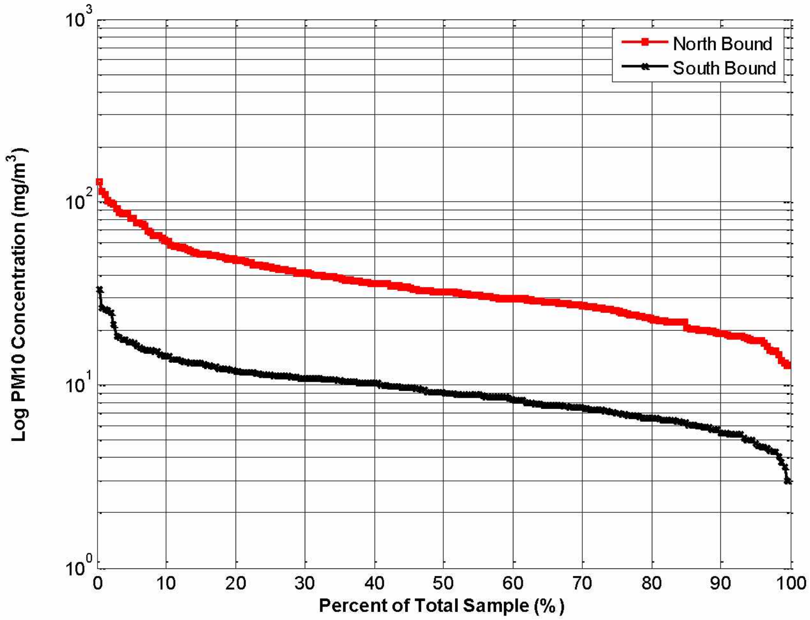

Figure 18 – PM_{10} concentrations recorded during a UAF-DUSTM test performed on Tweedy Road in Casa Grande, Arizona. The concentrations recorded when travelling in the north bound direction are signifigantly greater than the concentrations recorded when travelling in the south bound direction.

The moisture content of the soil affects PM_{10} emissions from gravel surfaces. There is an inverse relationship between soil moisture content and PM_{10} emissions. As soil moisture content increases the concentration of PM_{10} emissions decreases. Relative humidity can be used as an indication of soil moisture content. Relative humidity controls the rate of evaporation of moisture from the soil. If there is a high relative humidity the evaporation rate will be slow. If there is a low relative humidity the soil moisture can evaporate rapidly.

As relative humidity increases the concentration of PM_{10} measured with the UAF-DUSTM has a tendency to decrease. For example, UAF-DUSTM tests conducted on dust palliative treated roads in Eagle, Alaska, on 6/3/2011 and 6/4/2011 indicate a decrease in median concentration with an increase in relative humidity. Table 3 includes the median PM_{10} concentration from each UAF-DUSTM test and the relative humidity recorded during testing. The data suggests that there is an inverse relationship between PM_{10} concentrations and relative humidity, similar to the relationship between soil moisture content and PM_{10} concentrations.

Figure 19 is a scatter plot of median PM_{10} concentration versus relative humidity for the palliative treated sections used during UAF-DUSTM tests conducted in Eagle, Tetlin, and North Pole, Alaska. A power-series provides the best model of the data. It is expected that the data would follow a power series due to how the capillary forces develop in the soil. As the relative humidity decreases the soil moisture likely decreases. At low soil moisture contents there is not enough liquid in the void space to completely coat the particles and develop strong capillary forces. The coefficient of determination (R^2) for the model is equal to 0.1466 This is a low R^2 value, suggesting that the relative humidity does not have a significant effect on median PM_{10} concentration readings for dust palliative treated sections.

Table 3 - Results of UAF-DUSTM tests conducted on several roads in Eagle, Alaska.

Date	Test Section	Median PM_{10} Concentration (mg/m^3)	Relative Humidity (%)
6/3/2011	Amundsen	10.3	23.2
	Mission	5.66	27.7
	Third	2.73	22.0
	Control	28.4	21.6
6/4/2011	Amundsen	7.84	48.6
	Mission	3.96	48.9
	Third	1.67	44.7
	Control	21.3	50.4

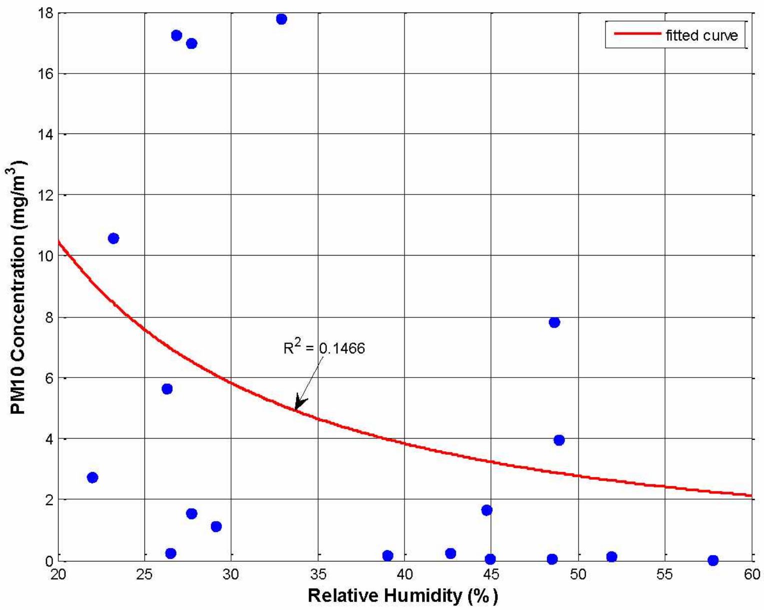

Figure 19 - Median PM_{10} Concentrations vs. Relative Humidity for the dust palliative treated sections used during UAF-DUSTM testing in Eagle, North Pole, and Tetlin, Alaska.

Further investigation of this dataset indicates the affect of relative humidity on median PM_{10} concentration is insignificant compared to the affect of ageing. An analysis of covariance (ANOCOVA) can be completed on the dataset by grouping median PM_{10} concentration versus relative humidity data based on the dust palliative's age when the test was conducted. Figure 20 is the ANOCOVA Prediction Plot for this data, showing the relationship between median PM_{10} concentration and relative humidity for each year. Note there was only one fourth year data point for median PM_{10} concentration versus relative humidity available and it is ignored in this analysis.

A linear model is fit to the entire dataset and each grouping of data. The coefficient estimates for each model are provided in Table 4. The models appear to be significantly different. Based on the grouping of the data, it appears that the median PM_{10} concentration increases each year, regardless of the relative humidity during testing.

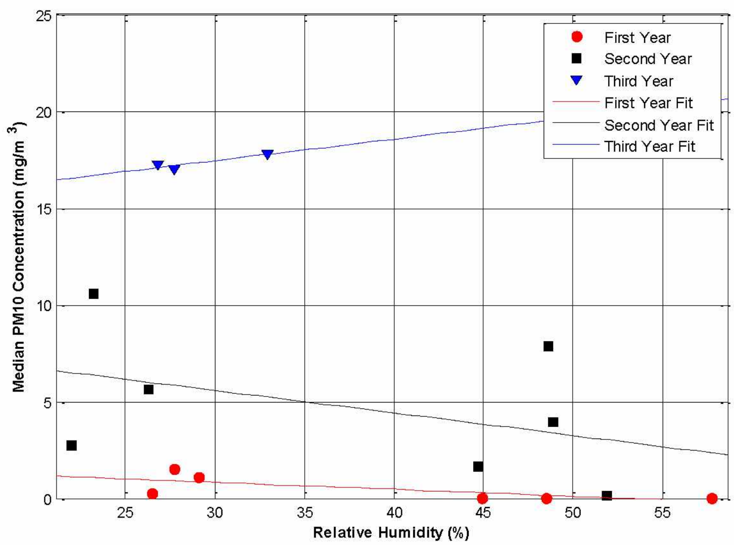

Figure 20 - ANOCOVA Prediction Plot for Median PM_{10} Concentrations vs. Relative Humidity

Table 4 – Estimated coefficients for the linear models used during ANOCOVA.

Term	**Estimate**	**Standard Error**	**T**	**Prob > |T|**
Intercept				
All Data	6.303	4.2701	1.48	0.1707
First Year	1.908	4.9703	-0.88	0.3976
Second Year	9.0577	4.8098	0.57	0.5795
Third Year	14.085	12.223	0.64	0.5386
Slope				
All Data	-0.0132	0.1887	-0.07	0.9454
First Year	-0.0226	0.1954	-0.12	0.910
Second Year	-0.1027	0.194	-0.53	0.6082
Third Year	0.0125	0.3712	0.34	0.7427

Figure 21 is a scatter plot of median PM_{10} concentration values versus the relative humidity during testing for the control sections in Eagle, North Pole, and Tetlin, Alaska, as well as Casa Grande, Arizona. Using a power series provides the best fit of the data, with a coefficient of determination (R^2) equal to 0.4842. There is a better correlation between median PM_{10} concentrations versus relative humidity for the untreated control sections compared to the dust palliative treated sections. PM_{10} concentrations are closely grouped when there is a higher relative humidity. In dry conditions the PM_{10} concentrations are more dispersed, suggesting that the influence of other environmental factors is greater.

There is a significant difference in how relative humidity effects a dust palliative treated section versus an untreated section. Again, this illustrates how the soil matrix behaves differently once a dust palliative is introduced to the system. These results also suggests that dust palliative performance cannot be determined by comparing results from a treated section to an untreated section as discussed previously.

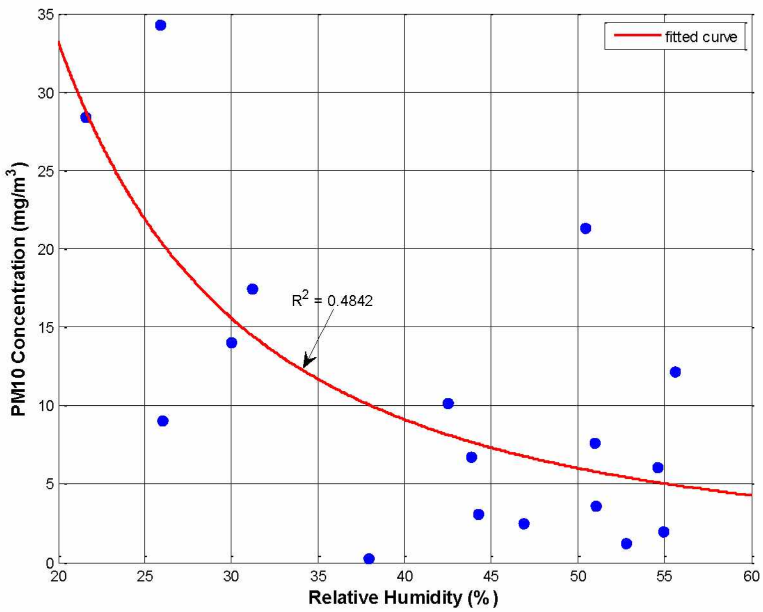

Figure 21- Median PM_{10} Concentrations vs. Relative Humidity for the control sections used during UAF-DUSTM testing in Eagle, North Pole, and Tetlin, Alaska, as well as Phoenix, Arizona.

Relative humidity may also influence the dispersion and transport of the dust plume generated by the ATV. Dispersion will be greater in arid conditions with low relative humidity. The air is less dense in these conditions and particles will have more freedom to disperse from the sources. When there is a high relative humidity the particles are more confined in the plume. Therefore it is expected that higher concentrations could be measured when the relative humidity is high. However, this effect has not be observed during testing. The impact of soil moisture content, inferred in terms of relative humidity, has a much greater affect and makes the influence of relative humidity on the dispersion of the dust plume insignificant.

4. Dust Palliative Effectiveness and Longevity

The following section provides an analysis of dust palliative effectiveness and longevity for three locations in Alaska: Eagle, Tetlin, and North Pole. The section is used to provide an example of how UAF-DUSTM results should be interpreted. Dust palliatives were applied to gravel roads in Eagle, AK and North Pole, AK during the summer of 2010. A dust palliative was applied to the runway in Tetlin, AK during the summer of 2009. These three sites provide the most complete datasets for evaluating dust palliative performance and longevity and provide examples of the strengths and limitations of the UAF-DUSTM as discussed in the previous section. Box plots are used to present the results of each UAF-DUSTM test. Tables are provided that contain a summary of the descriptive statistics used in creating the figures in this section including: the first quartile, the median, the third quartile.

4.1 Eagle, Alaska

A dust palliative was applied to several gravel roads in Eagle, Alaska, during June 2010 by the AKDOT&PF. The dust palliative, EnviroKleen®, is manufactured by Midwest Industrial Supply, Inc. The dust palliative was applied at a rate of 1 gallon per 40 square feet, as recommended by the manufacturer. UAF-DUSTM tests were conducted on 8/4/2010, 6/3/2011, 6/4/2011, and 6/22/12.

Amundsen Street, Mission Road, and Third Avenue were selected as representative test sections to evaluate the effectiveness and longevity of the dust palliative application. This decision was based on the varying surface condition of each road and the anticipated traffic volume. Amundsen and Mission are defined as rural major collectors by the AKDOT&PF Functional Classification Update (AKDOT&PF, 2010b). Amundsen Road begins at the end of the Taylor Highway and continues north through town to the Yukon River. Mission Road connects the town of Eagle to Eagle Village and residential housing outside of the town limits. Mission Road begins at the Bureau of Land Management (BLM) Visitor Center on the west edge of Eagle and continues east, following the Yukon River. Mission Road is also known as First Avenue and Front Street. Amundsen Road and Mission Road are bordered by residential and commercial areas. Third Avenue is an arterial road that connects Amundsen Road and Mission Road. The local school is located on Third Avenue as well as residential housing. A section of Eagle Road was used for the untreated control section. Table 5 provides the latitude and longitude of the beginning and end of each test section.

Table 5 - Latitude and longitude coordinates for the beginning and end of each test section in Eagle, Alaska.

Test Section:	**Location:**	**North:**	**West:**
Amundsen Street	Beginning of Test Section	64°47.274'	141°12.177'
	End of Test Section	64°47.666'	141°13.905'
Mission Road	Beginning of Test Section	64°46.853'	141°09.700'
	End of Test Section	64°47.280'	141°12.120'
3rd Avenue	Beginning of Test Section	64°47.102'	141°11.852'
	End of Test Section	64°47.234'	141°12.375'
Control	Beginning of Test Section	64°46.241'	141°06.287'
	End of Test Section	64°46.245'	141°04.210'

Figure 22 provides the box plots of PM_{10} concentrations measured on the control section, Eagle Road. The results are summarized in Table 6. During the summer of 2010 Eagle experienced heavy rains, which may explain the increase of PM_{10} concentrations on the control section in 2011 and 2012. The difference in PM_{10} concentrations between 6/03 and 6/04/2011 can be explained by the timing of each test. The tests on 6/03/2011 were conducted in the afternoon; after any dew that had penetrated the road surface during the evening and night had been evaporated. The tests on 6/04/2011 were conducted during the morning hours. This trend is consistent for each test section. The UAF-DUSTM tests conducted on 6/22/2012 represent the greatest PM_{10} emission potential, and will be used to evaluate the effectiveness and longevity of the dust palliative applications.

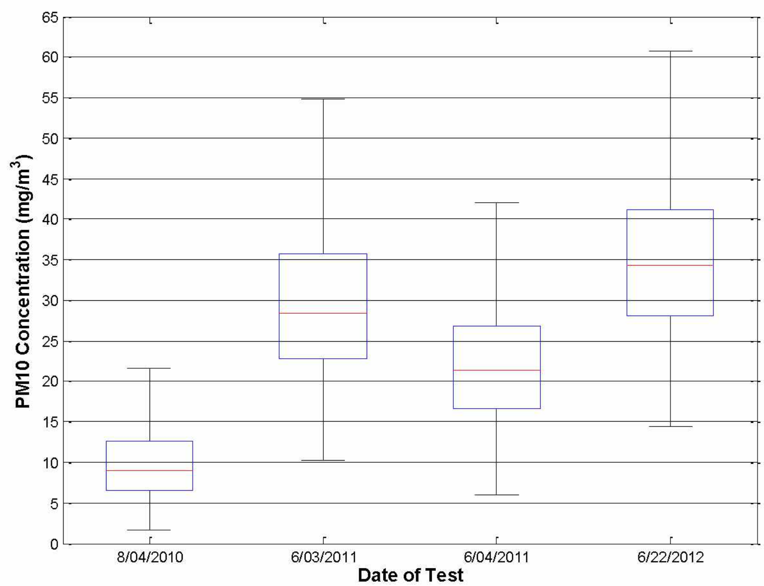

Figure 22 - Box plot of PM_{10} concentrations measured on the control section used in Eagle, Alaska.

Table 6 - Summary of PM_{10} concentrations measured on the control section in Eagle, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/4/2010	6.52	9.05	12.60
6/3/2011	22.80	28.50	35.70
6/4/2011	16.60	21.30	26.80
6/22/2012	28.15	34.30	41.20

Figure 23 provides the box plot of PM_{10} concentrations measured on Amundsen Street. The results are summarized in Table 7. Based on the results from 8/04/2010, the dust palliative initially provided a reduction of PM_{10} emissions compared to the control section. There is a large increase in PM_{10} concentrations between 2010 and 2011. PM_{10} concentrations continue to increase in 2012; however the majority of PM_{10} concentrations are less than those measured on the control section in 2012. The third quartile of PM_{10} concentrations measured on Amundsen Road in 2012 was 25.60 mg/m^3. The first quartile of PM_{10} concentrations measured on the control section in 2012 was 28.15 mg/m^3. This suggests that the dust palliative is still providing a reduction in PM_{10} emissions.

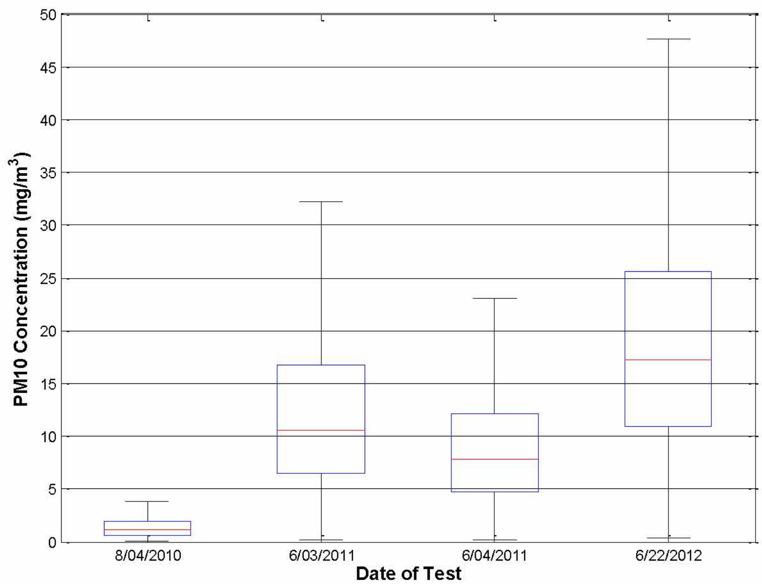

Figure 23 - Box plot of PM_{10} concentrations measured on Amundsen Street in Eagle, Alaska.

Table 7 - Summary of PM_{10} concentration measured on Amundsen Road in Eagle, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/4/2010	0.64	1.14	4.97
6/3/2011	6.49	10.60	16.80
6/4/2011	4.71	7.84	12.10
6/22/2012	10.90	17.25	25.60

Figure 24 provides the box plots of PM_{10} concentrations measured on Mission Road. The results are summarized in Table 8. Based on the results from 8/04/2010, the dust palliative initially provided a reduction of PM_{10} emissions compared to the control section. The PM_{10} concentrations increase in 2011 and again in 2012. Similar to Amundsen Street, the PM_{10} concentrations measured on Mission Road in 2012 are less than those measured on the control section in 2012. This suggests that the dust palliative is still providing a reduction in PM_{10} emissions.

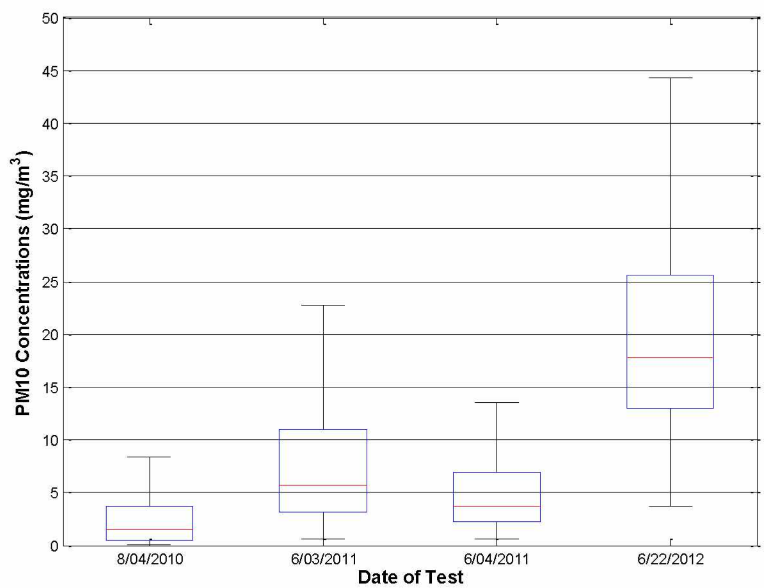

Figure 24 - Box plot of PM_{10} concentrations measured on Mission Road in Eagle, Alaska.

Table 8 - Summary of PM_{10} concentration measured on Mission Road in Eagle, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/4/2010	0.50	1.54	3.67
6/3/2011	3.14	5.66	11.00
6/4/2011	2.29	3.69	6.88
6/22/2012	13.00	17.80	25.60

Figure 25 provides the box plots of PM_{10} concentrations measured on Third Avenue. The results are summarized in Table 9. Based on the results from 8/04/2010, the dust palliative initially provided a reduction of PM_{10} emissions compared to the control section. The PM_{10} concentrations increase in 2011 and again in 2012. The PM_{10} concentrations measured on Third Avenue in 2012 are less than those measured on the control section in 2012. This suggests that the dust palliative is still providing a reduction in PM_{10} emissions.

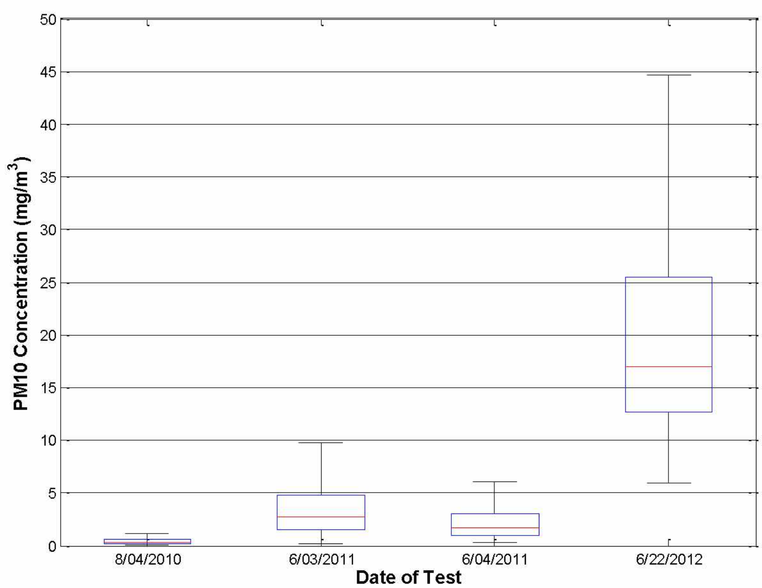

Figure 25 - Box plot of PM_{10} concentrations measured on Third Avenue in Eagle, Alaska.

Table 9 - Summary of PM_{10} concentrations measured on Third Avenue in Eagle, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/4/2010	0.15	0.26	0.58
6/3/2011	1.50	2.73	4.82
6/4/2011	0.96	1.67	3.00
6/22/2012	12.70	17.00	25.50

From the results of the UAF-DUSTM tests conducted in 2012 it appears that the dust palliative application is still providing a reduction in PM_{10} emissions compared to the untreated control section. The first and third quartile PM_{10} concentrations are similar for each dust palliative treated sections. This suggests that the dust palliative effectiveness is decreasing uniformly regardless of the location of the test section within Eagle and differences in traffic volume.

4.2 North Pole, Alaska

Several gravel roads in North Pole, Alaska, were treated with dust palliatives between 7/28/2010 and 8/03/2010. The roads, located in the Moose Meadows road service area of the Fairbanks North Star Borough, included: Sharon Road, Moosewalk Road, Plack Road, Blackstone Road, and Plato Avenue. The roads were not prepped before application besides the annual grading and repairs completed at the beginning of summer. This was done to mimic the conditions found in rural villages in Alaska, where heavy equipment is not often available. It was immediately clear that the dust palliative application on Blackstone Road was a failure. Plato Way was regraded after application due to a miscommunication with the road service area manager, destroying the dust palliative application. Table 10 summarizes the dust palliative applications for the remaining roads.

Durasoil®, manufactured by Soilworks® LLC, was applied to Sharon Road using a ten foot spray bar with nozzles spaced every foot. Freedom-Binder 400, manufactured by Freedom Industries Inc. was applied using a 6,000 gallon water truck. Dustaway®, another product manufactured by Soilworks ® LLC, was also applied using the 6,000 gallon water truck. Dawson Road was selected as the untreated control section used for determining dust palliative performance. The first UAF-DUSTM tests were conducted on 8/12/2010. The last UAF-DUSTM tests were conducted on 6/01/2011.

Table 10 - Summary of the dust palliatives application for the test site in North Pole, Alaska.

Test Site	**Product**	**Treated Length (feet)**	**Application Rate (ft^2/gal)**	**Application Date**
Sharon	Durasoil	2475	30	7/28/10
Moosewalk	Freedom-Binder 400	1980	7.2	8/2/10
Plack	Dustaway	2165	9	8/3/2010

Figure 26 provides the boxplots of PM_{10} concentration measured from the untreated control section on Dawson Road. The results are summarized in Table 11. The largest PM_{10} concentrations were measured on 8/17/2010. There was a significant decrease in PM_{10} concentrations between 8/17/2010 and 9/12/2010. This decrease is likely due to precipitation. Between 8/17 and 9/12/2010 a total of 1.53 inches of rain were measured at the National Oceanic and Atmospheric Administration (NOAA) weather station located in North Pole. There was no rain between 9/12/2010 and the test on 9/20/10 (NCDC, 2012). The observed increase in PM_{10} concentrations is likely due to the evaporation of soil-water added by the rain event

On 9/12, 9/13/ and 9/17/2012, UAF-DUSTM tests were conducted during the morning and afternoon. The difference in PM_{10} concentrations between the morning and afternoon tests on these dates are likely caused by the drying of moisture from the gravel surface throughout the day. This trend is also seen on the dust palliative treated sections. The PM_{10} concentrations measured on 6/01/2011 were similar to those measured on 8/12 and 8/17/2010. These three dates represent the worst potential for PM_{10} emissions. The effectiveness and longevity of the dust palliative applications may be inferred by comparing to these dates.

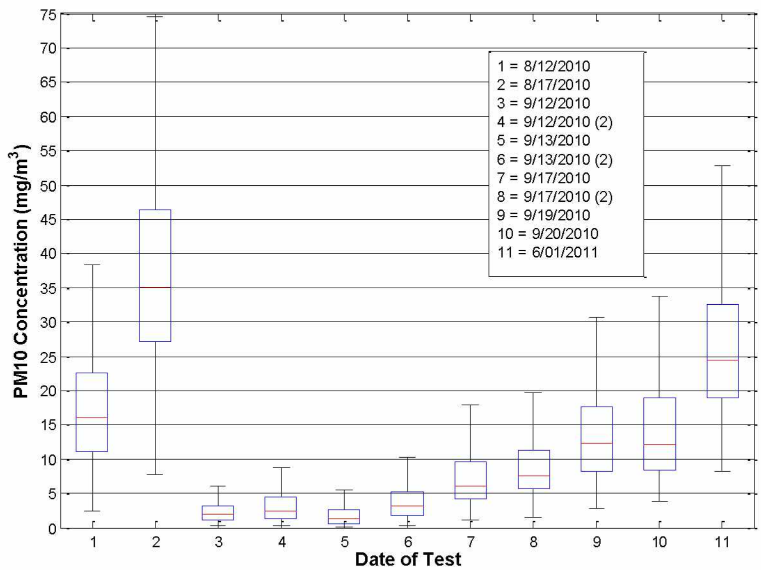

Figure 26 - Box plot of PM_{10} concentrations measured on Dawson Road in North Pole, Alaska.

Table 11 - Summary of PM_{10} concentration measured on Dawson Road in North Pole, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/12/2010	11.20	16.10	22.60
8/17/2010	27.18	35.10	46.30
9/12/2010	1.17	1.99	3.15
9/12/2010 (2)	1.35	2.50	4.44
9/13/2010	0.54	1.21	2.57
9/13/2010 (2)	1.75	3.13	5.19
9/17/2010	4.11	6.06	9.67
9/17/2010 (2)	5.64	7.61	11.37
9/149/2010	8.28	12.40	17.60
9/20/2010	8.42	12.10	19.00
6/01/2011	18.90	24.40	32.50

Figure 27 provides box plots of the PM_{10} concentrations measured on Moosewalk Road during the 2010 testing season. Figure 28 contains the box plot of the PM_{10} concentrations measured on 6/01/2011, which were excluded from Figure 27 for clarity. The results are summarized in Table 12. From results it is clear that the effectiveness of the dust palliative applied to Moosewalk Road began to decrease within two months of the initial application. The median PM_{10} concentration on 8/12/2010 was 0.41 mg/m^3. The median PM_{10} concentration was 1.13 mg/m^3 on 9/12/2010. The rain events between 8/17/2010 and 9/12/2010 did not have as big of an impact on the PM_{10} concentrations compared to control section. The other dust palliative treated sections exhibit the same behavior. The PM_{10} concentrations measured on Moosewalk Road on 6/01/2011 are comparable to the largest PM_{10} concentrations measured on the control section, shown in Figure 26. Based on these results it is assumed the dust palliative has completely failed and is no longer providing a reduction in PM_{10} emissions. The longevity of the dust palliative is less than one year.

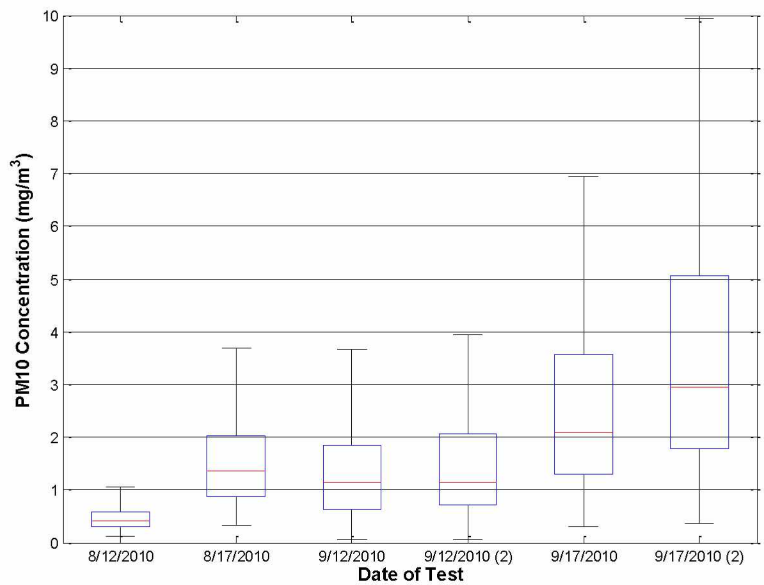

Figure 27 - Box plot of PM_{10} concentrations measured during 2010 on Moosewalk Road in North Pole, Alaska.

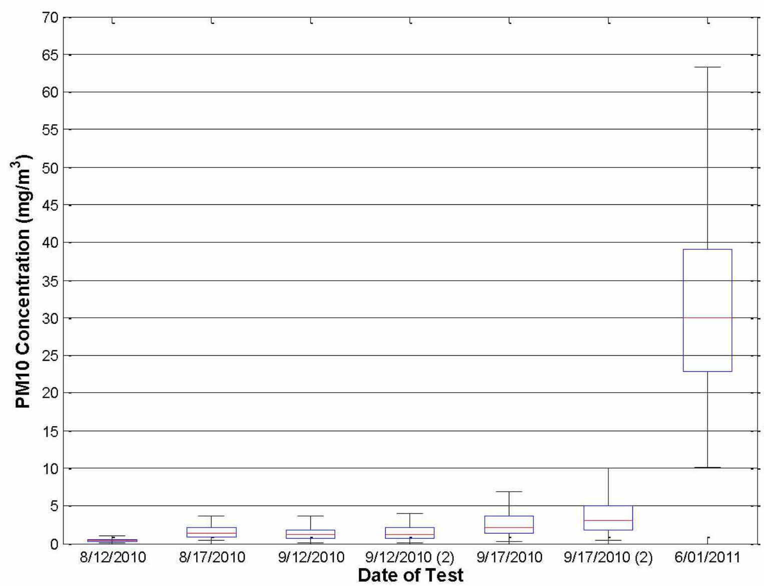

Figure 28 - Box plot of PM_{10} concentrations measured during 2010 and 2011 on Moosewalk Road in North Pole, Alaska.

Table 12 - Summary of PM_{10} concentrations measured on Moosewalk Road in North Pole, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/12/2010	0.29	0.41	0.59
8/17/2010	0.87	1.35	2.03
9/12/2010	0.62	1.13	1.84
9/12/2010 (2)	0.73	1.14	2.08
9/17/2010	1.29	2.09	3.57
9/17/2010 (2)	1.78	2.95	5.05
6/01/2011	22.85	29.95	39.15

Figure 29 contains the boxplots of PM_{10} concentrations measured on Sharon Road between 8/12/2010 and 6/01/2011. The results are summarized in Table 13. There is a significant difference between the PM_{10} concentrations measured on Sharon Road and the PM_{10} concentrations measured on the control section. The dust palliative applied to

Sharon Road was very effective in reducing PM_{10} emissions. While there was an increase in PM_{10} concentrations after the winter months, the PM_{10} concentrations are still significantly less than those measured on the untreated control section. This confirms that the dust palliative's longevity is at least one year. However, while the dust palliative continued to perform well, the surface conditions of the road declined. The road had to be regraded to provide a better driving surface, preventing measurements beyond the first year. This illustrates the importance of proper road design and construction when developing dust management strategies. In order to be cost effective the dust palliative has to provide dust control for several years. If the road fails the dust palliative's full potential in terms of longevity cannot be reached.

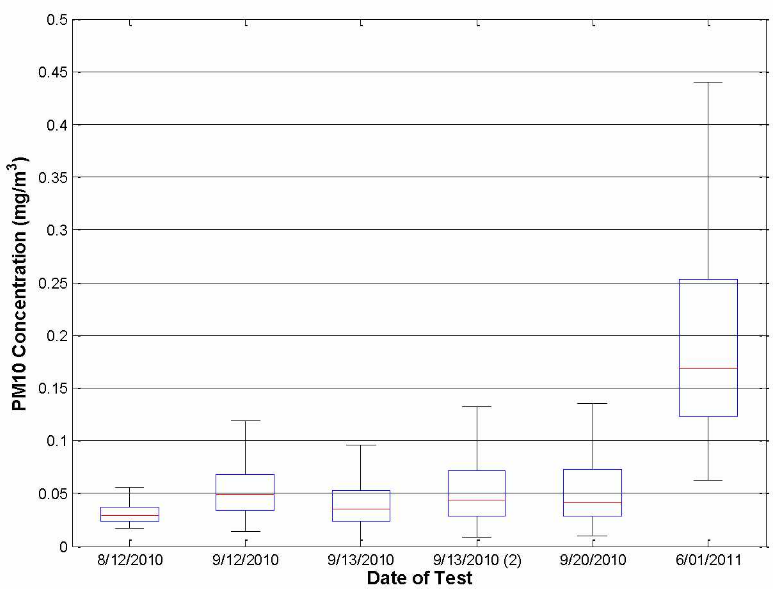

Figure 29 - Box plot of PM_{10} concentrations measured on Sharon Road in North Pole, Alaska.

Table 13 - Summary of PM_{10} concentrations measured on Sharon Road in North Pole, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/12/2010	0.024	0.029	0.037
9/12/2010	0.034	0.049	0.068
9/13/2010	0.024	0.035	0.053
9/13/2010 (2)	0.028	0.044	0.071
9/20/2010	0.029	0.042	0.072
6/01/2011	0.123	0.169	0.253

Figure 30 provides the box plots of PM_{10} concentrations measured on Plack Road. The results are summarized in Table 14. Based on the figure it is clear that the dust palliatives effectiveness began to decrease within two months of the initial application. The PM_{10} concentrations measured on 6/01/2011 are comparable to the largest PM_{10} concentrations measured on the control section. Based on these results it is assumed the dust palliative has completely failed and is no longer providing a reduction in PM_{10} emissions. The longevity of the dust palliative is less than one year.

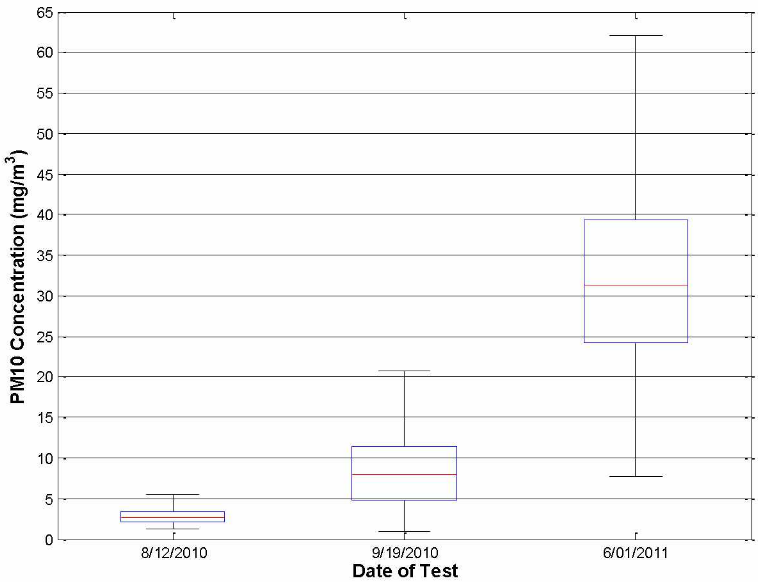

Figure 30 - Box plot of PM_{10} concentrations measured on Plack Road in North Pole, Alaska.

Table 14 - Summary of PM_{10} concentration measured on Plack Road in North Pole, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/12/2010	2.05	2.60	3.45
9/19/2010	4.78	8.00	11.50
6/01/2011	24.18	31.30	39.40

4.3 Tetlin, Alaska

The UAF-DUSTM results for the dust palliative application in Tetlin, Alaska, represent an anomaly compared to the other sites. Durasoil® was applied to the gravel runway in Tetlin, Alaska, in June 2009. The first UAF-DUSTM tests, conducted in 2009, were completed using a $PM_{2.5}$ filter on the DustTrak, and will not be considered in this discussion. UAF-DUSTM tests were conducted in 2010, 2011, and 2012 using a PM_{10}

filter on the DustTrak. The runway thresholds were used as the beginning and end of each test for the treated and untreated sections. The control section is located on the shoulder of the runway, outside of the runway lights.

Figure 31 provides the box plots of PM_{10} concentrations measured on the control section used in Tetlin. The results are summarized in Table 15. The PM_{10} concentrations vary significantly between tests. Figure 32 provides the box plot of PM_{10} concentrations measured on the dust palliative treated section in Tetlin. The results are summarized in The PM_{10} concentrations measured on the dust palliative treated section are less than those measured on the control section. Again, the PM_{10} concentrations vary significantly between tests. The PM_{10} concentrations do not follow the trend of increasing PM_{10} concentrations observed at other sites. However, the PM_{10} concentrations measured on the untreated and treated sections do follow a similar trend. This suggests that the measurements were consistently influenced by some environmental parameter.

Figure 33, Figure 34, and Figure 35 are wind roses of the data recorded during UAF-DUSTM tests on 8/10/2010, 6/05/2011 and 6/21/2012 respectively. Weather data for 8/11/2010 is not available. For each day of testing the wind was predominately from the West. This represents a headwind when the UAF-DUSTM tests were travelling west bound and a tail wind when the UAF-DUSTM tests were travelling east bound. The magnitudes of the wind speeds are similar for each day. Based on these results it is assumed that the difference between the PM_{10} concentrations for each test is not due to the influence of wind.

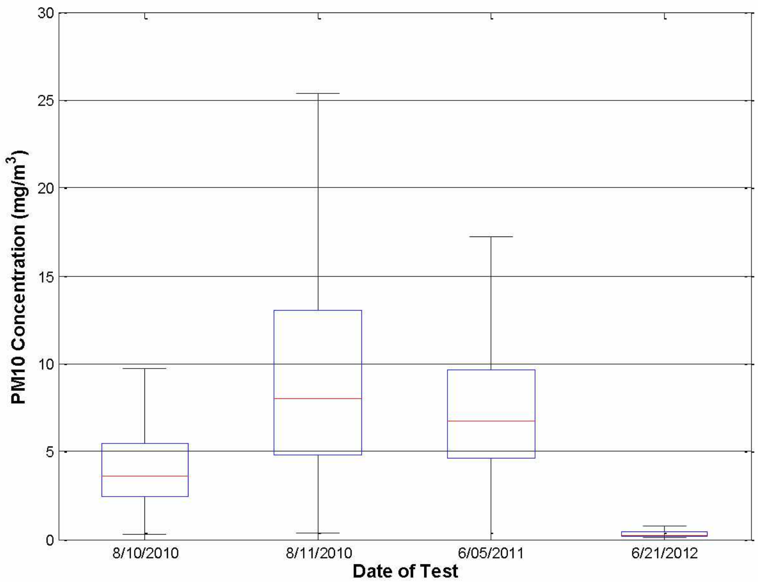

Figure 31 - Box plot of PM_{10} concentrations measured on the untreated control section of the runway in Tetlin, Alaska.

Table 15- Summary of PM_{10} concentration measured on the untreated control section of the runway in Tetlin, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/10/2010	2.44	3.64	5.46
9/11/2010	4.81	8.02	13.05
6/05/2011	4.64	6.76	9.70
6/21/2012	0.18	0.26	0.42

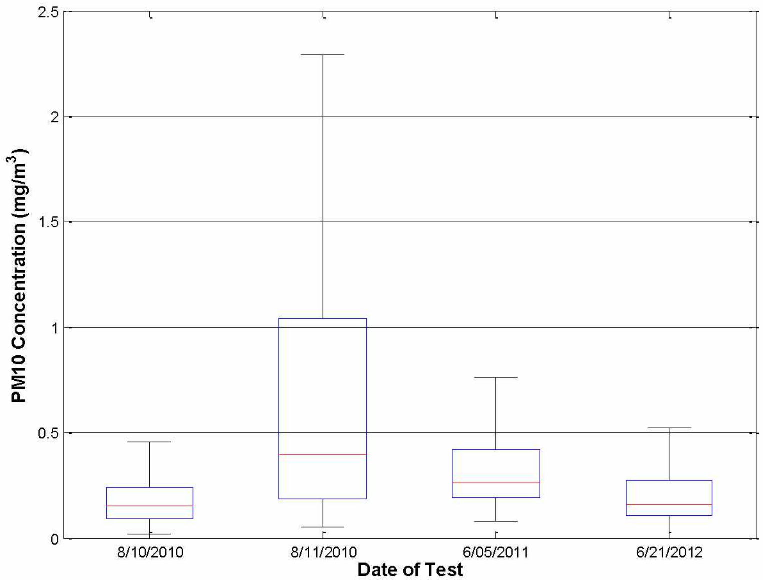

Figure 32 - Box plot of PM_{10} concentrations measured on the dust palliative treated section of the runway in Tetlin, Alaska.

Table 16 - Summary of PM_{10} concentration measured on the dust palliative treated section of the runway in Tetlin, Alaska.

Date	First Quartile (mg/m3)	Median (mg/m3)	Third Quartile (mg/m3)
8/10/2010	0.093	0.153	0.242
9/11/2010	0.185	0.397	1.04
6/05/2011	0.190	0.263	0.419
6/21/2012	0.107	0.158	0.274

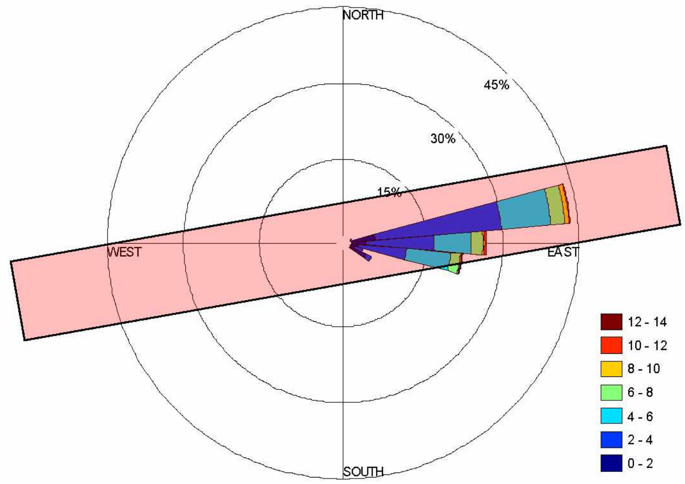

Figure 33 - Wind data in miles per hour recorded during UAF-DUSTM testing on the runway located in Tetlin, Alaska, on 8/10/2010. The box overlaid plot represents the orientation of the runway relative to the wind data.

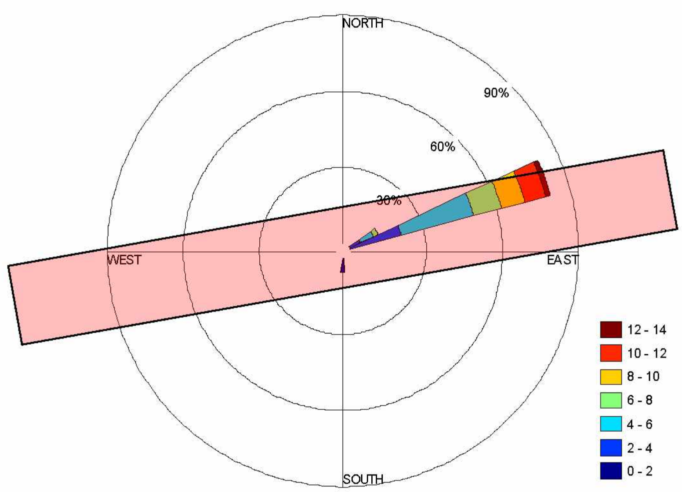

Figure 34 - Wind data in miles per hour recorded during UAF-DUSTM testing on the runway located in Tetlin, Alaska, on 6/05/2011. The box overlaid plot represents the orientation of the runway relative to the wind data.

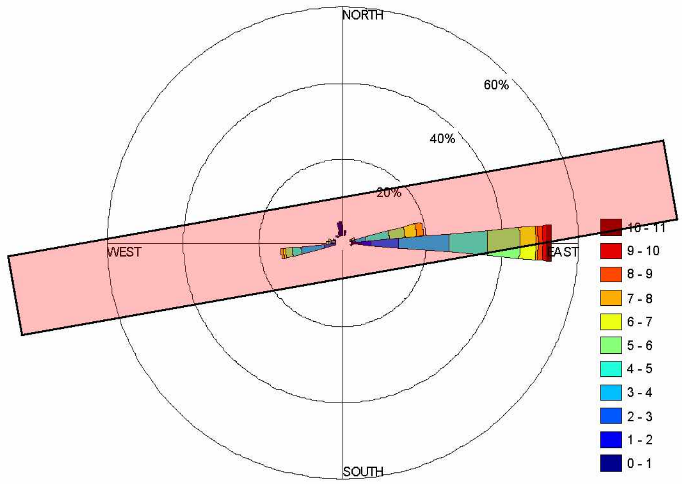

Figure 35 - Wind data in miles per hour recorded during UAF-DUSTM testing on the runway located in Tetlin, Alaska, on 6/22/2012. The box overlaid plot represents the orientation of the runway relative to the wind data.

Table 17 contains the median PM_{10} concentrations and average relative humidity measured during the UAF-DUSTM tests on the control section in Tetlin. The lowest median PM_{10} concentration corresponds with the lowest relative humidity measurement. This does not agree with the expected inverse relationship discussed previously. Based on these results it is assumed that the difference between the PM_{10} concentrations for each test is not due to the influence of relative humidity.

Table 17 - Median PM_{10} concentrations and relative humidity data recorded during UAF-DUSTM tests in Tetlin, Alaska.

Date	Median Concentration (mg/m^3)	Average Relative Humidity (%)
8/10/2010	3.64	51.0
6/05/2011	6.76	43.8
6/12/2012	0.258	37.9

The difference in PM_{10} concentrations may be due to the moisture content of the gravel surface during testing. Moisture content samples were not collected during testing. Precipitation data recorded prior to testing may be used to infer soil moisture content, but there are no weather stations within a 100 mile radius of Tetlin with precipitation data during this period. The construction and soil characteristics of the runway may also have affected measurements. Tetlin is a relatively new runway compared to the other sites investigated during this study. It is a road accessible site which means it can be properly maintained by skilled operators using ideal construction equipment. There is little airplane traffic in Tetlin due to its road accessibility, which reduces the wear on the dust palliative application. The soils in the area typically have higher clay contents then other parts of the state. High clay contents will reduced PM_{10} emissions and may affect how the dust palliatives behave chemically in the soil Additional testing and investigation is required in Tetlin before the effectiveness and longevity of the dust palliative can be evaluated.

5. Conclusions

During the development of the UAF-DUSTM several limitations were identified. Currently the UAF-DUSTM cannot be used to determine dust palliative effectiveness in terms of an absolute reduction in PM_{10} emissions. Instead a holistic approach must be used to analyze the PM_{10} concentrations measured on a dust palliative treated section to infer dust palliative effectiveness and longevity. While this may limit the use of the UAF-DUSTM it remains a useful tool in developing dust management strategies. It can be used to monitor dust palliative applications as they age, helping engineers and road managers develop an understanding of how specific palliatives behave in their area.

The results of this research have shown that dust palliatives can successfully be used to manage fugitive dust emissions from gravel surfaces. However, there are several factors which may cause dust palliative to fail prematurely. During the course of this study several dust palliative failures were observed that were likely caused by an improper application. The success of a dust palliative application depends on several factors including: the environmental conditions during application; the gradation, moisture content, and level of compaction of the soil during application; and the equipment used to apply the dust palliative.

Environmental conditions such as freezing temperatures and precipitation events during application will negatively impact the dust palliative and should be avoided. This makes it difficult to schedule dust palliative applications in Alaska. Often the dust palliative application is the last work item to be completed in a contract and occurs during the early to late fall. This time of year is typically characterized by low temperatures and rain or snow. Scheduling dust palliative applications for the following summer after construction is completed will ensure that the dust palliative can be applied during optimal conditions.

The soil characteristics during application also influence the success of the dust palliative application. Some dust palliatives require that the soil be moist so the dust palliative can break the surface tension and penetrate further into the surface. Others require the soil to be as dry as possible so the dust palliative can spread across the soil particle surface. Dust palliatives should not be applied unless the soil is at the proper moisture content. If the surface is too compact the dust palliative will not be able to penetrate into the soil matrix and coat particles. Developing laboratory based tests will ensure that the proper dust palliative is selected and the application occurs when soils are at the optimal condition.

There are several different techniques and types of equipment available for applying dust palliatives. The equipment should provide as much control over the application as possible. A distribution system consisting of a spray bar with evenly spaced nozzles is ideal, as it provide a uniform application across the surface. If a controlled distribution system is not available field tests using water should be conducted first . Factors such as the number of passes required, the number of gallons for each pass, and the time between each pass should be determined before the dust palliative application begins.

Dust palliatives will continue to be used to control fugitive dust emissions. Further investigation into how these dust palliatives behave in the soil matrix is required to develop a better understanding of how they reduce fugitive dust emissions. Understanding these fundamentals will aid engineers in selecting the proper dust palliative. A standard testing method for determining dust palliative effectiveness, both field based and laboratory based, is essential to ensure successful applications are achieved.

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